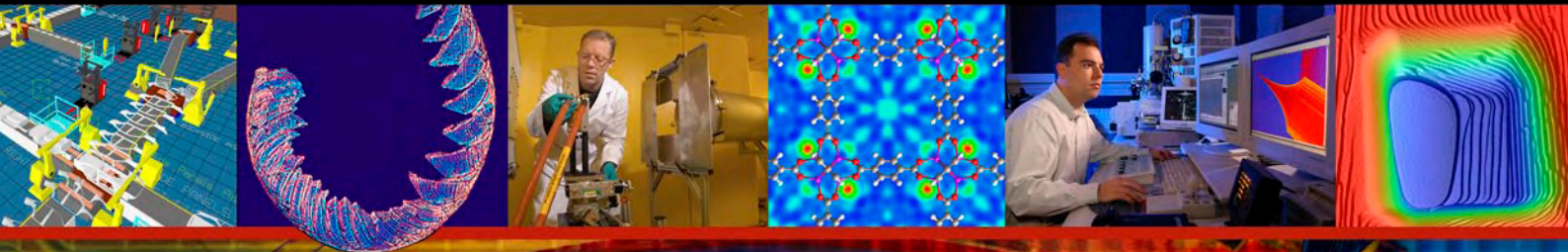


MANUFACTURING THE FUTURE



Report of the
Interagency Working Group on Manufacturing R&D
Committee on Technology
National Science and Technology Council

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About the National Science and Technology Council

The National Science and Technology Council (NSTC) was established by Executive Order on November 23, 1993. This cabinet-level council is the principal means by which the President coordinates science, space, and technology policies across the Federal Government. NSTC coordinates diverse paths of the Federal research and development enterprise.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research to improving transportation systems and strengthening fundamental research. The Council prepares research and development strategies that are coordinated across the Federal agencies to form a comprehensive investment package aimed at accomplishing multiple national goals. For more information visit http://www.ostp.gov/nstc/html/NSTC_Home.html

About the Interagency Working Group on Manufacturing Research and Development

The Interagency Working Group (IWG) on Manufacturing Research and Development (R&D) serves as a forum within the NSTC Committee on Technology for developing consensus and resolving issues associated with manufacturing R&D policy, programs, and budget guidance and direction.

The chartered goal of the IWG on Manufacturing R&D, which was formed in 2004, is to identify and integrate requirements, conduct joint program planning, and develop joint strategies for the manufacturing R&D programs conducted by the Federal government. The IWG serves as a forum for the exchange and leverage of information among the participating agencies.

For more information on the IWG on Manufacturing R&D, see <http://www.manufacturing.gov>

About this document

This report of the IWG on Manufacturing R&D outlines three areas of opportunity for manufacturing R&D and describes critical manufacturing technology issues that need to be addressed in each area in order to make progress. The report also describes Federal activities in the three areas and current and planned collaborative efforts. Finally, the report provides an overview of important cross-cutting issues that affect R&D for all three areas.

Cover and book design

Cover images right to left: Etched silicon for measuring step heights (NIST); Examining a probe tip with an atomic resolution microscope (NIST); Molecular model and neutron scattering image of possible hydrogen fuel storage compound (NIST); Preparing a fuel cell for real-time imaging with neutrons (© Robert Rathe); Machined chip cross-section for metallographic analysis (NIST); Simulation of manufacturing floor (NIST); NIST Nanofabrication Facility (© Robert Rathe); Polymer-carbon nano tube composite (NASA); Portable, non-contact 3D-laser scanner used to create of a 3D solid model (NIST); Computer model of a carbon nanotube “decorated” with titanium atoms (NIST); Magnesium oxide cubes sprinkled with gold nanoparticles (NIST); A colorized lattice of tornado-like vortices within a spinning Bose Einstein condensate of rubidium atoms. (NIST)

Manufacturing the Future

Federal Priorities for Manufacturing R&D



Report of the

Interagency Working Group on Manufacturing R&D

Committee on Technology

National Science and Technology Council



March 2008

Report prepared by

National Science And Technology Council Committee On Technology (CT) Interagency Working Group (IWG) On Manufacturing R&D

CT Chair: Richard Russell, Associate Director, Office of Science and Technology Policy

CT Executive Secretary: Jason Boehm, Department of Commerce (DOC) /
National Institute of Standards and Technology (NIST)

IWG Chair

Dale Hall, DOC/NIST

IWG Executive Secretary

David Stieren, DOC/NIST*

Office of Science and Technology Policy (OSTP)

Celia Merzbacher*

Susan Skemp

Department and Agency Representatives

Department of Agriculture (USDA)

Hongda Chen*

Karen Hunter*

DOC/International Trade Administration (ITA)

Timothy Miles*

DOC/NIST

David Stieren*

Dale Hall

Department of Defense (DOD)

Adele Ratcliff*

Department of Education (ED)

Richard LaPointe*

Scott Hess

Department of Energy (DOE)

Harvey Wong*

Jacques Beaudry-Losique

Doug Faulkner

Department of Health and Human Services (DHHS)/National Institutes of Health (NIH)

Belinda Seto*

Department of Homeland Security (DHS)

Richard Kikla*

John Kubricky

Maurice Swinton

Department of Labor (DOL)

Steven Rietzke*

Tom Dowd*

Michael Jaffe

Jennifer McNelly

Department of Transportation (DOT)

William Chernicoff*

Ashok Kaveeshwar

Environmental Protection Agency (EPA)

Diana Bauer*

Stephen Lingle

National Aeronautics and Space Administration (NASA)

John Vickers*

Ralph Carruth

Gweneth Smithers

National Science Foundation (NSF)

Adnan Akay*

George Hazelrigg*

Warren Devries

Linda Blevins

Kevin Lyons

Office of Management and Budget (OMB)

Andrea Petro

Melissa Brandt

Office of Science and Technology Policy (OSTP)

Celia Merzbacher*

Susan Skemp

Small Business Administration (SBA)

Edsel Brown*

Karen Hontz

* These individuals are the current agency points of contact for this IWG on Manufacturing R&D at the time of publication of this report. The other individuals listed here are no longer active on the IWG, but contributed to the production of this report.

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

March 11, 2008

Dear Colleagues:

I am pleased to forward with this letter a report on Federal research and development (R&D) efforts in the area of manufacturing. The Federal government plays an important role in the funding of R&D in advanced and novel manufacturing processes, devices, and systems. Moreover, through its support for university and other post-secondary education, the Federal government also helps develop a skilled workforce that is able to translate the results of manufacturing R&D into practical application.

This report highlights three areas of opportunity in manufacturing R&D that have been identified by the Interagency Working Group (IWG) on Manufacturing R&D under the National Science and Technology Council's Committee on Technology. The areas are (1) manufacturing for the hydrogen economy; (2) nanomanufacturing; and (3) intelligent and integrated manufacturing. These areas align with the Administration's R&D priorities and are consistent with the President's American Competitiveness Initiative.

A healthy manufacturing sector is very important to the U.S. economy and to our national security. Progress in the areas outlined in this report, in conjunction with policies to transition the results of Federally-funded research into practical application, will help to ensure a robust U.S. manufacturing sector into the future.

Sincerely,



John H. Marburger, III
Director



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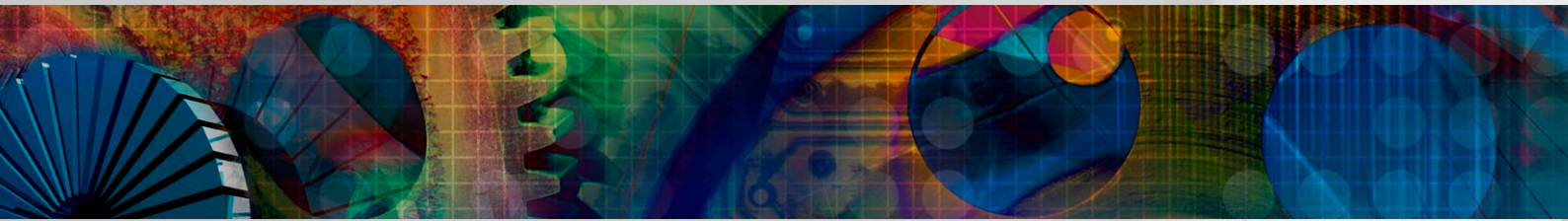
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Executive Summary



Manufacturing R&D in the United States

Manufacturing is the transformation of materials into goods. That transformation may use people, capital, processes, systems, and enterprises, to deliver products of value to society. The value may be wealth, strategic capability for defense and security, or the resources for art, literature, and other domains of culture. Manufacturing is both a key economic sector by itself and, in the context of manufacturing research and development, a critical enabler of other economic sectors.

Manufacturing research and development (R&D) focuses on improving the productivity of the manufacturing enterprise. Manufacturing R&D also yields processes for making new materials, devices, and systems, as well as processes for delivering manufactured goods precisely, when and where needed. In today's global environment, time is a critical competitive factor. Manufacturing R&D must go hand-in-hand with scientific discovery to ensure that U.S. manufacturers can quickly transform innovations into processes and products.

The accelerating pace of scientific discovery and technological innovation is setting the stage for a new set of manufacturing transformations worldwide. Advances in information technology, nanotechnology, biotechnology, and other fields are creating tremendous opportunities for economic, social, and environmental benefits. Realizing these benefits will require advanced manufacturing capabilities enabled by new processing methods, equipment, predictive models, and other tools that will result from manufacturing-related R&D.

In today's environment, the U.S. manufacturing sector faces new opportunities as well as new challenges, many of which were conveyed in the 2004 Commerce Department report, *Manufacturing in America*.¹ How effectively U.S. manufacturers can respond to these challenges depends on actions on many fronts and on different scales, from individual businesses to industries to government. There is strong consensus in industry, academia, and government that the future competitiveness of U.S. manufacturing — and all that it underpins — will be determined, in large part, by research, innovation, and how quickly firms and industries can apply and incorporate new technologies into

high-value-added products and high-efficiency processes.²

The Interagency Working Group (IWG) on Manufacturing Research and Development established by the National Science and Technology Council (NSTC) has identified three technology areas as areas of opportunity today for Federal manufacturing R&D:

1. Manufacturing R&D for Hydrogen Technologies
2. Nanomanufacturing
3. Intelligent and Integrated Manufacturing

These areas were selected based on their current and future importance to the Nation's economic and national security. The areas also leverage scientific and technological advances that are enabling the transformation of knowledge and materials into products of significant value to society. Much of the work in these areas falls under the American Competitiveness Initiative. In addition, each area also corresponds to existing priorities established by the Administration and the NSTC: the Hydrogen Fuel Initiative, the National Nanotechnology Initiative (NNI), and the Networking and Information Technology Research and Development Program (NITRD).

¹ U.S. Department of Commerce, *Manufacturing in America: A Comprehensive Strategy to Address the Challenges to U.S. Manufacturers*, January 2004, available at <http://www.ita.doc.gov/media/Publications/pdf/manuam0104final.pdf>.

² In addition to *Manufacturing in America*, recent assessments recommending increased national emphasis on research and innovation include Council on Competitiveness National Innovation Initiative, *Innovation: The New Reality for National Prosperity: 21st Century Innovation Working Group Recommendations*, December 2004, available at http://www.compete.org/docs/pdf/NIIL_21st_Century_Innovation_20Report.pdf; The Task Force on the Future of American Innovation, *The Knowledge Economy: Is the United States Losing Its Competitive Edge?* February 2005, available at <http://futureofinnovation.org/reports/>; and American Electronics Association, AeA, *Losing the Competitive Advantage? The Challenge for Science and Technology in the United States*, February 2005, available at http://www.aeanet.org/publications/idxj_CS_overview.asp.

Manufacturing R&D for Hydrogen Technologies aims for the reliable manufacture of hydrogen production, storage solutions, and fuel cell components and systems. The ultimate goal is to replace petroleum with hydrogen to power our light-duty vehicles, leading to energy security and virtual elimination of vehicular emissions of pollutants and greenhouse gases. Low-cost, high-volume manufacturing processes and development of a domestic supplier base are necessary to develop hydrogen fuel infrastructure and affordable fuel cell vehicles.

Nanomanufacturing R&D is directed toward enabling the mass production of reliable and affordable nanoscale materials, structures, devices, and systems. Nanotechnology is viewed throughout the world as a critical driver of future economic growth and as a means to addressing some of humanity's most vexing challenges. Because of its broad range of prospective uses, nanotechnology has the potential to impact virtually every industry, from aerospace and energy to healthcare and agriculture. Nanomanufacturing includes the integration of ultra-miniaturized top-down processes and evolving bottom-up or self-assembly processes.

Intelligent and Integrated Manufacturing (IIM) R&D encompasses work on the application of advanced software, controls, sensors, networks, and other information technologies to achieve rapid, cost-predictive development of innovative products and processes and highly efficient production machines and systems that can be easily adapted and reconfigured in response to changing requirements and new opportunities. As such, the IIM priority area is broad in scope; it encompasses mid-

to long-term R&D in support of essentially all manufacturing-specific applications of emerging information technologies. The overall objective is to enable and encourage transformational applications to improve the production, business, and interorganizational capabilities of U.S. manufacturers, regardless of size or where they reside in the supply chains and collaborative, networked enterprises of the future.

These areas of research are interdependent: advances in one can contribute to progress in the others. For example, the design and cost-effective production of nanomaterials to store hydrogen may be critical to the transition away from an oil-dependent transportation system. Similarly, "intelligent," flexible manufacturing tools will be required to design, manufacture, and integrate nanoscale components into affordable products and systems for real-world applications. And for the U.S. manufacturing sector as a whole, the capability to integrate new designs, processes, and materials in a flexible fashion will translate into competitive advantages ranging from shorter product development cycles to new value-added products and services.

This report outlines three areas of opportunity for manufacturing R&D and describes critical manufacturing technology issues that need to be addressed in each area in order to make progress. The report also describes Federal activities in the three areas and current and planned collaborative efforts. Finally, the report provides an overview of important cross-cutting issues that affect R&D for all three areas: workforce preparation, health and safety, environmental sustainability, and standards.

Acknowledgments

The Interagency Working Group (IWG) on Manufacturing Research and Development (R&D) extends its thanks to the agency representatives listed on page ii for their invaluable contributions to preparation of this report. A number of other key contributors were instrumental in developing initial draft white papers and relevant reports and in conducting reviews of Federal research and development in the three technical priority focus areas of the IWG. Task team leaders who guided the development of the content for the three focus areas were

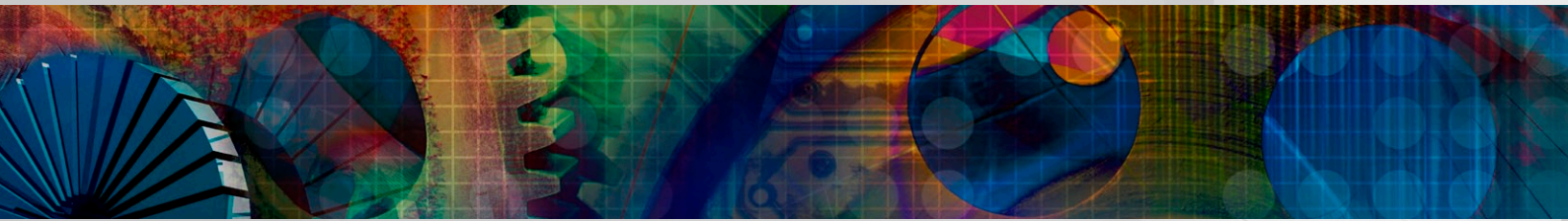
- *Manufacturing R&D for Hydrogen Technologies*: JoAnn Milliken, Department of Energy
- *Nanomanufacturing*: Warren DeVries, National Science Foundation
- *Intelligent and Integrated Manufacturing*: Albert Wavering, National Institute of Standards and Technology (NIST)

This report references an IWG-sponsored public forum that was held on March 3, 2005, and a follow-on workshop to initiate development of a roadmap on manufacturing R&D for the hydrogen economy, which was conducted July 13–14, 2005. The IWG wishes to express its gratitude to the Department of Commerce, Department of Energy, and NIST for sponsoring these forums. Special thanks are extended on behalf of the IWG and the forum sponsors to all the participants at the public forums and those who provided comments via the IWG website (see www.manufacturing.gov), via email, and as attendees at the numerous conferences and meetings where members of the IWG were invited to present its activities.

This document was sponsored by NIST. Special thanks for the technical writing, editing, and final production of the report are due to NIST staff members Mark Bello and David Stieren; Steve Bushby and Dale Hall provided helpful editorial comments; and Beamie Young contributed significantly to graphics and layout.

Chapter 1

Introduction



What Is Manufacturing R&D?

The National Science and Technology Council (NSTC) Interagency Working Group (IWG) on Manufacturing R&D definition of “manufacturing R&D” encompasses basic and applied experiments and investigations (as well as associated technical activities that include testing, prototype development, and other early-stage work). These focus on nascent or emerging technologies that have the potential to significantly improve existing manufacturing methods or processes; lead to entirely new — and, perhaps, revolutionary — processes, machines, or systems; or enable production of innovative or high-value-added products. Ultimately realized improvements may include more rapid production, increased yields, increased accuracy and precision, defect reduction, reduced costs, more efficient utilization of capital and resources, and reduced environmental impact. In the context of the Federal Government, these outcomes may result, directly or indirectly, from research efforts to develop advanced capabilities that further the missions of Federal agencies.

Manufacturing R&D Focuses on

- Unit process-level technologies that improve manufacturing processes, such as machining, deposition, layering, molding, or joining
- New processes, such as those required to manufacture heterogeneous 3D nanotechnology products
- Machine-level technologies and systems that improve manufacturing productivity, quality, flexibility, or safety for such tasks as fabrication, assembly, or inspection
- Systems-level technologies for innovation in the manufacturing enterprise, including controls, sensors, radio-frequency identification (RFID), networks, and information technologies; technologies that support logistics and transportation pathways and infrastructure; and methods and approaches that improve design and decision making and integrated and collaborative product and process development
- Insight and understanding that improves workforce abilities, sustainability, or manufacturing competitiveness; anticipates and responds to global labor, health and safety, and environmental objectives; anticipates and responds to global and domestic availability of energy and materials; and informs supporting investments in energy, communication, information, and communication infrastructure

The Federal Role in Research and Development

The Federal Government is the Nation's largest supporter of basic research, accounting for about 61% of the total investment. Industry, in contrast, devotes about 4% of its R&D dollars to basic research and accounts for about 16% of the total national investment in this category. States and nonprofit institutions account for most of the Nation's remaining investment here.³ Some economists estimate that as much as half of post-World War II economic growth is due to R&D-fueled technological progress.⁴ Today's revolutionary technologies and many of our most popular consumer products have roots deep in basic and applied research, much of it funded by Federal investment.

The Federal Government continues to focus on basic research in order to protect and promote future American competitiveness and well-being. In February 2006, President Bush announced the American Competitiveness Initiative (ACI) to support basic research and world-leading facilities in the physical sciences to enable future breakthroughs and provide economic security benefits.⁵

³ National Science Foundation, *Science and Engineering Indicators 2006*, www.nsf.gov/statistics/seind06/

⁴ Office of Science and Technology Policy Domestic Policy Council, *American Competitiveness Initiative: Leading the World in Innovation*, February 2006, p. 4, available online at www.whitehouse.gov/stateoftheunion/2006/aci/aci06-booklet.pdf.

⁵ *Ibid.*

The centerpiece of the ACI is the strong commitment to doubling investment over ten years in key Federal agencies that support basic research programs in the physical sciences and engineering. Over ten years, the ACI proposes an increase of nearly \$50 billion in innovation-enabling research to advance the kinds of knowledge and technological capabilities that can have broad scientific impact and maximum economic benefit.

The ACI is built upon recognition that sustained scientific advancement and innovation are key to the United States maintaining a competitive edge, and that scientific advancement must be supported by a pattern of related investments and policies that include support for cutting-edge basic physical science research. It also recognizes that investments must occur within a business environment that stimulates and encourages entrepreneurship through flexible labor, capital, and product markets that rapidly diffuse new productive technologies.

Productive, domestic R&D efforts are thus recognized in government policy at the highest levels as being key to ensuring that U.S. manufacturers will be able to compete effectively in the high-technology markets of the future and that other U.S. businesses, as well as U.S. consumers, will be among the first to benefit from new capabilities afforded by innovation.

In fiscal year (FY) 2006, total Federal funding for R&D was \$135.5 billion. Of that amount, \$27.4 billion in funding was for basic research, \$27.4 billion was for applied research, \$76.1 billion was for development, and \$4.5 billion was for facilities and equipment R&D.⁶ Industry analysis estimates that in 2006, industry invested \$212 billion on R&D, with academia and nonprofit organizations spending \$20.4 billion.⁷

⁶ Office of Management and Budget, Executive Office of the President, "Analytical Perspectives, Budget of the U.S. Government," 2008, p.51, available at <http://www.whitehouse.gov/omb/budget/fy2008/apers.html>.

⁷ Battelle, "2006 R&D Funding Forecast," *R&D Magazine*, January 2006.

The Interagency Working Group on Manufacturing R&D

Guided by the above logic and by the imperatives set out in *Manufacturing in America*, in May 2004, the NSTC's Committee on Technology created the IWG on Manufacturing R&D to help coordinate and prioritize the Federal investment in manufacturing-related research. The IWG consists of representatives from the 15 Federal departments and independent agencies listed in Table 1-1.

In general terms, the IWG on Manufacturing R&D is a chartered forum within the NSTC to address manufacturing R&D policy and programmatic issues.

About this Report

This report summarizes the initial steps of the IWG toward accomplishing its chartered objectives (Table 1-2) and describes its planned next steps. It characterizes the Federal role in manufacturing R&D and details three technological areas the IWG has identified as having potential to deliver major benefits, from new jobs to enhanced manufacturing competitiveness to tangible progress toward accomplishing major national goals. Given this potential, the IWG supports prioritizing R&D these areas. Last, the report addresses several critical social issues that cut across all three areas. In this report, "IWG" refers to the Interagency Working Group on Manufacturing R&D.

Since its inception, the IWG has worked to ensure an appropriate Federal R&D focus on innovation and productivity-enhancing manufacturing technologies. Consistent with its chartered objectives (Table 1-2), and following budget guidance issued by the Offices of Science and Technology Policy and Management and Budget, the IWG has aimed to "maximize the coordination and planning" of agency R&D programs and to complement existing interagency R&D priorities.⁸

⁸ John H. Marburger and Joshua B. Bolten, "FY 2007 Administration Research and Development Budget Priorities," M-05-18, July 8, 2005. See <http://www.whitehouse.gov/omb/memoranda/fy2005/m05-18.pdf>.

Table 1-1: IWG Membership

U.S. Department of Agriculture (USDA)
<ul style="list-style-type: none"> • Cooperative State Research, Education, and Extension Service (CSREES)
U.S. Department of Commerce (DOC)
<ul style="list-style-type: none"> • National Institute of Standards and Technology (NIST) • International Trade Administration (ITA)
U.S. Department of Defense (DOD)
<ul style="list-style-type: none"> • Office of the Secretary of Defense (OSD)
U.S. Department of Education (ED)
<ul style="list-style-type: none"> • Office of Educational Technology (OET)
U.S. Department of Energy (DOE)
<ul style="list-style-type: none"> • Office of Energy Efficiency and Renewable Energy (EERE) • National Nuclear Security Administration (NNSA)
U.S. Department of Health & Human Services (DHHS)
<ul style="list-style-type: none"> • National Institutes of Health (NIH)
U.S. Department of Homeland Security (DHS)
<ul style="list-style-type: none"> • Science and Technology Directorate (S&T)
U.S. Department of Labor (DOL)
<ul style="list-style-type: none"> • Employment and Training Administration (ETA)
U.S. Department of Transportation (DOT)
<ul style="list-style-type: none"> • Research and Innovative Technology Administration (RITA)
U.S. Environmental Protection Agency (EPA)
<ul style="list-style-type: none"> • Office of Research and Development (ORD)
National Aeronautics and Space Administration (NASA)
<ul style="list-style-type: none"> • Marshall Space Flight Center (MSFC)
National Science Foundation (NSF)
<ul style="list-style-type: none"> • Directorate for Engineering
Office of Management & Budget (OMB)
Office of Science and Technology Policy (OSTP)
U.S. Small Business Administration (SBA)
<ul style="list-style-type: none"> • Office of Government Contracting and Business Development (OGCBD)

Table 1-2: Chartered Functions of the IWG on Manufacturing R&D

1. Propose policy recommendations for manufacturing R&D.
2. Engage in interagency manufacturing R&D program planning and budgeting and, where appropriate, develop and promote opportunities for interagency coordination of manufacturing R&D that address identified gaps.
3. Review agency priorities and technical issues for Federally funded manufacturing R&D.
4. Promote communications with the private sector and academia to address existing and long-term R&D requirements and programs.
5. Identify opportunities for interagency collaboration, coordination, and leverage in specific technical areas related to manufacturing R&D.
6. Report annually to the Committee on Technology and to the President's Office of Science and Technology Policy (OSTP), summarizing IWG activities and setting forth recommendations regarding the establishment of Federal manufacturing R&D priorities and the need for specific interagency activities to address those priorities.
7. Identify potential connections and synergies between manufacturing and other Federally supported research.

Manufacturing R&D Technical Areas of Opportunity

Building on earlier work done under the Government Agencies Technology Exchange in Manufacturing (GATE-M), the IWG carried out analyses in 2004–5 of manufacturing R&D priorities by agency. The results assisted the IWG in defining its initial focus to be coordination of three priority interdisciplinary R&D areas with extensive potential to benefit U.S. industry and the Nation's economy:

1. Manufacturing R&D for Hydrogen Technologies
2. Nanomanufacturing
3. Intelligent and Integrated Manufacturing

The areas are summarized in the boxes below and described in detail in Chapters 2–4 of this report.

Manufacturing R&D for Hydrogen Technologies

Manufacturing R&D for hydrogen technologies aims for the reliable manufacture, in large quantities, of components and their assembly into products that can be used to produce, deliver, store, and use hydrogen via fuel cells.

Replacing petroleum with hydrogen to power cars and trucks is a long-term national goal, intended to help achieve energy security and virtually eliminate vehicular emissions of pollutants and greenhouse gases. This goal is being pursued under the President's Hydrogen Fuel Initiative, launched in 2004 to accelerate development of hydrogen and fuel cell technologies.

Meeting cost targets so that affordable fuel cell vehicles and the hydrogen fuel infrastructure to support them can be developed requires low-cost, high-volume manufacturing processes. In the area of hydrogen production, key needs include standardizing component and system designs, as well as overcoming technical challenges associated with the delivery of hydrogen. Among storage-related challenges are requirements for high-volume production of storage tanks, now made with composite materials in a labor-intensive process. Before fuel cells can be mass-produced, numerous manufacturing challenges and needs must be addressed. These range from transforming proof-of-concept, laboratory-scale technologies into rugged, reliable products made with standardized fuel cell components.

Nine of the IWG's member agencies participate in the Hydrogen Fuel Initiative. Through their involvement in the IWG, these agencies and other organizations, including industry and academia, have contributed to the development of a manufacturing R&D roadmap for the hydrogen economy⁹, a collaborative activity led by the Department of Energy in conjunction with the IWG.

Considerations related to manufacturing R&D for hydrogen technologies are addressed in more detail in Chapter 2.

⁹ Department of Energy, Roadmap on. Manufacturing R&D for the Hydrogen Economy, 2005, available online at http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf.

Nanomanufacturing

Nanomanufacturing is defined by the IWG as all manufacturing activities that collectively support an approach to design, produce, control, modify, manipulate, and assemble nanoscale elements or features with dimensions of roughly 1 to 100 nanometers for the purpose of realizing a product or system that exploits properties that arise at the nanoscale.

Nanomanufacturing R&D is directed toward enabling the mass production of reliable and affordable nanoscale materials, structures, devices, and systems. This includes the integration of ultra-miniaturized top-down processes and evolving bottom-up or self-assembly processes.

Nanotechnology is viewed throughout the world as a critical driver of future economic growth and as a means to solving some of humanity's most vexing challenges. Because of its incredibly broad range of prospective uses, nanotechnology has the potential to impact virtually every industry, from aerospace and energy to healthcare and agriculture.

Realizing this potential depends on progress on many fronts of science and engineering. Ultimately, it will require reliable tools and processes for precisely manipulating and assembling the basic building blocks of nanotechnology products, cost-effectively producing these products in large quantities, and integrating them into systems spanning nanoscale to large-scale dimensions. In addition, nanotechnology could have profound structural implications for the manufacturing sector in general.

Nanomanufacturing considerations are addressed in more detail in Chapter 3.

Intelligent and Integrated Manufacturing

The IWG defines intelligent and integrated manufacturing (IIM) as the application of advances in software, controls, sensors, networks, and other information technologies to achieve

- Rapid, cost-predictive development of innovative products and processes
- Highly productive, safe, and secure production machines and systems that are easily adapted and reconfigured in response to changing conditions and new opportunities
- Optimized, agile, and resilient enterprises and supply chains

Information technology (IT) continues to reshape nearly all facets of manufacturing, from product development and design through distribution and post-sale customer support. Exponential increases in computing power and the increasing availability and diversity of inexpensive sensors and other networked devices usher in new opportunities to build processes and configure organizations in ways that optimize capabilities, performance, and value. At the same time, the incredible power, utility, and adaptability of still-emerging IT systems introduce new layers of complexity and create new potential vulnerabilities in terms of security risks and software errors.

IIM is fundamental to the advanced manufacturing operations and organizations of tomorrow. It also is critical to progress toward a hydrogen-powered economy, for national security, innovative real-world applications of nanotechnology, as well as other national goals.

Intelligent and integrated manufacturing considerations are addressed in more detail in Chapter 4.

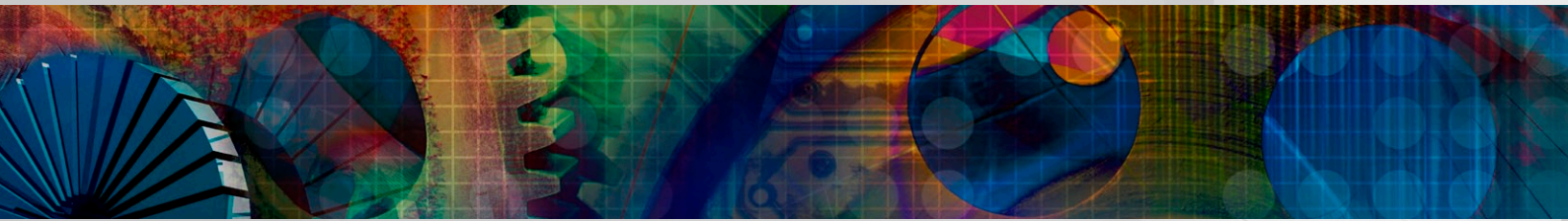
While each of the three areas of opportunity individually rises to the level of national importance, together, they are highly interdependent, thus promising beneficial synergies and elevating their combined importance. Advances in one are expected to contribute to progress in the others. For example, the design and cost-effective production of nanomaterials that efficiently store hydrogen are viewed as key to the transition away from an oil-dependent transportation system. Similarly, “intelligent” manufacturing tools will be required to design, manufacture, and integrate nanoscale components into affordable products and systems for real-world applications, including practical hydrogen fuel cells. And for the manufacturing sector as a whole, the ability to integrate new designs, processes, and materials in a modular fashion will translate into competitive advantages that include shorter product development cycles, more efficient and more flexible supply chains, and new opportunities to deliver value-added products and services to customers.

Besides the technological R&D challenges and opportunities of the three areas described above, there are several related cross-cutting social and technical issues that are significant. These pertain to workforce preparation, human health and safety, environmental sustainability, and setting of measurable and enforceable standards. The IWG is working to understand and, where appropriate, address these important considerations, which are described in more detail in Chapter 5 of this report.

Multiagency task teams established by the IWG for each technical area have assessed manufacturing needs and challenges in each technology domain and weighed prospective benefits to be realized from a coordinated, multiagency focus on manufacturing R&D. More details on the assessment of the three task teams may be found in Chapters 2–4.

Chapter 2

Manufacturing R&D for Hydrogen Technologies



Definition and Scope

The IWG defines manufacturing R&D for hydrogen technologies as the reliable manufacture, in large quantities, of components — and their assembly into products — used to produce, deliver, store, and use hydrogen via fuel cells.

The IWG technical priority area Manufacturing R&D for Hydrogen Technologies complements the President's Hydrogen Fuel Initiative, which President Bush unveiled in 2003. The Hydrogen Fuel Initiative commits \$1.2 billion over five years (2004–2008) to reverse the Nation's growing dependence on foreign oil by developing the technology needed to establish commercially viable hydrogen-powered fuel cells — a means to power cars, trucks, homes, and businesses without producing pollution or greenhouse gases. The initiative is the largest component of a comprehensive R&D effort that will help pave the way to widespread use of hydrogen and fuel cell technologies. In addition to several other Federal programs, the effort leverages the FreedomCAR and Fuel Partnership, a joint undertaking involving U.S. automakers, five energy companies, and the Department of Energy. Also, the Interagency Working Group on Hydrogen and Fuel Cells, which involves twelve Federal agencies and is co-chaired by DOE and the White House Office of Science and Technology Policy, is coordinating Federal efforts to develop the advanced materials and many other enabling technologies integral to achieving the hydrogen economy.¹⁰

¹⁰ For more information see <http://www.hydrogen.gov>.

Manufacturing R&D is one among many areas being addressed by the President's Hydrogen Fuel Initiative and the Hydrogen R&D Interagency Task Force. The IWG on Manufacturing R&D is working closely with both programs to complement their efforts and to sharpen the focus given to manufacturing R&D as a critical enabler for the widespread use of hydrogen as an energy carrier. Through such coordination, the IWG seeks to accelerate the development of the necessary technologies and infrastructure to enable manufacturing for hydrogen and fuel cell components and systems.

Many scientific, technical, and institutional challenges must be overcome before hydrogen can replace fossil fuels and be integrated into the Nation's economic and energy infrastructures. The complexity of these challenges is illustrated by the scope of the changes that will be required in the passenger segment of the Nation's vehicular transportation system. These include lowering the cost of hydrogen production and delivery; lowering the cost and improving the capacity limitations of current hydrogen storage systems; lowering the cost and improving the performance and durability of current fuel cell systems; lowering the cost of integration and ensuring near-zero defect standards in manufacturing, all accompanied by appropriate institutional supports for high levels of safety over the lifetimes of all components.

Overcoming these obstacles will require progress in science and engineering on many fronts. Ultimately, however, achieving the vision of a hydrogen economy will depend largely on the Nation's manufacturing capabilities, that is, on whether U.S. industry can develop high-volume, cost-effective processes for making the fuel cells and related production, delivery, and storage technologies that are now in their infancy. Given the pivotal role that manufacturing must play if the United States is to realize the energy and environmental benefits of deploying hydrogen and fuel cell systems, it is critical that manufacturing R&D occur simultaneously while the technologies are still being developed. As critical hydrogen and fuel cell technologies become ready for commercialization, manufacturing processes must be developed concurrently to (1) reduce the costs of hydrogen systems to levels that are competitive with today's petroleum-based systems, (2) build the necessary manufacturing infrastructure to support the hydrogen economy, and (3) to develop a domestic supplier base for hydrogen and fuel cell components.

The IWG concurs with the National Research Council's assessment of DOE's FreedomCAR and Fuel Partnership, which underscored the challenges related to manufacturing R&D in the following statement:

The development of commercially viable fuel cells and onboard hydrogen storage is, without question, the most difficult vehicular aspect of this program. Multiple challenges are being addressed: performance, durability, efficiency, and cost, and they are being worked on at all levels: basic technology, the individual components, stacks, and systems. For fuel cells, durability and cost are the most difficult goals, and for hydrogen storage, the most difficult are size, weight, and cost. In most instances, solutions depend on yet-to-be-conceived or -proven component and manufacturing technology rather than incremental improvement.¹¹

Federal R&D and Coordination Efforts

Since identifying manufacturing R&D for hydrogen technologies as a priority for Federal R&D, the IWG — with DOE as lead agency — has followed up with actions to sharpen the manufacturing focus of ongoing R&D activities, improve planning, and foster greater awareness and synergy across agencies. The IWG has also chartered a Community of Interest (COI) on Manufacturing for Hydrogen Energy Technologies to serve as a forum within the IWG for conducting joint program planning and developing joint agency strategies for Federal R&D programs related to manufacturing for hydrogen energy technologies. This COI has fostered significant communication among member agencies that has influenced agency decision making processes regarding investments in this area. Largely through interactions within the IWG, member agencies have begun greater collaboration in developing manufacturing technologies for hydrogen systems. Agencies have also built partnerships with industry, a vital collaborator going forward.

Several IWG member agencies are actively pursuing a number of efforts that address the many different aspects of manufacturing R&D and technology that are critical to hydrogen production and delivery, hydrogen storage, and fuel cells. The principal agency leading manufacturing R&D programs related to transitioning to the hydrogen economy is DOE; DOC/NIST, DOD, DOT, NSF, and other agencies play important supporting and partnership roles.

¹¹ National Academies of Science, *Review of the Research Program of the FreedomCAR and Fuel Partnership, First Report*, Washington, DC: National Academies of Science, 2005.

Department of Energy

DOE has consistently taken an approach to R&D for hydrogen technologies that deliberately addresses manufacturing issues. For example, its 2003 Fuel Cell Report to Congress¹² identifies the need to address manufacturing issues for fuel cells; It details its strategy for addressing manufacturing in its 2005 draft *Roadmap on Manufacturing R&D for the Hydrogen Economy*. More recently, DOE issued an R&D solicitation in 2007 for Manufacturing for Hydrogen and Fuel Cell Systems that, pending future Congressional appropriations over several years, will award up to \$38 million for projects in technologies nearing commercialization in areas such as membrane electrode assembly manufacturing and manufacturing technologies for high-pressure composite tank applications.¹³

DOE is advancing hydrogen technologies through multiple programs, including its Hydrogen Program; Hydrogen, Fuel Cells and Infrastructure Technologies Program; and the FreedomCAR and Fuel Partnership.¹⁴ Integral to many of the DOE programs is creation of manufacturing partnerships to address hydrogen-related R&D challenges

DOE's Fuel Cell Report to Congress, February 2003

- Core technology development should focus more attention on advanced materials manufacturing techniques and other advancements to lower cost, increase durability, and improve reliability of fuel cell systems.
- Public-private cooperative programs, where government and industry work together in a collaborative manner, provide a means to overcome commercialization barriers so that the national benefits can be realized.

National Institute of Standards and Technology

NIST Laboratories are providing measurements, data, and technologies needed to develop and test the performance of hydrogen-based power sources and to improve the efficiency of hydrogen production methods. NIST Lab efforts are focused on developing the innovative tools needed for assuring safe commercial production, storage, distribution, and delivery of hydrogen as an energy carrier in a hydrogen economy.

¹² http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf

¹³ http://www.hydrogen.energy.gov/news_manufacturing_funding.html

¹⁴ Information on these and other DOE hydrogen-related programs is available on its Hydrogen Program website at <http://www.hydrogen.energy.gov/>; its Hydrogen, Fuel Cells, and Infrastructure Technologies Program website at www1.eere.energy.gov/hydrogenandfuelcells/; and its FreedomCAR and Vehicle Technologies (FCVT) Program website at <http://www1.eere.energy.gov/vehiclesandfuels/index.html>.

Department of Transportation

DOT is responsible for establishing regulations and standards for vehicle safety, hydrogen transportation safety, pipeline safety, and related activities. In addition to ensuring safety in manufacturing components and processes, it must ensure safety in the distribution and supply chain related to hydrogen product manufacture. It is also developing the rigorous, technically grounded standards that are essential to ensure safety, reliability, and public confidence. In December 2006, DOE and DOT jointly published The Hydrogen Posture Plan for coordinated activities under the Hydrogen Fuel Initiative.

National Science Foundation

NSF is pursuing research contributing to the development of enabling technologies for hydrogen-based energy generation and storage. This includes activities within the NSF Division of Design, Manufacture, and Industrial Innovation under its Engineering Directorate, as well as activities within both the Chemistry and Materials Research Divisions of the NSF Mathematical and Physical Sciences Directorate.

Other Agencies

DOD, NASA, and USDA contribute in various ways to large-scale implementation of manufacturing solutions, despite not themselves leading significant R&D programs directly focused on manufacturing R&D for hydrogen technologies. These agencies' activities are focused on various complementary aspects of manufacturing R&D, and they bring their unique agency perspectives to bear on the challenges being addressed. Other agency programs that relate to Manufacturing R&D for Hydrogen Technologies include the DOD's Manufacturing Technology Program, as well as R&D and program efforts associated with the DOD Services and the R&D Division of the Defense Logistics Agency (see Table 2-1); the DOE Industrial Technologies Program; NASA's National Center for Advanced Manufacturing; and activities of NSF's Division of Design, Manufacture, and Industrial Innovation under its Engineering Directorate.

Table 2-1 summarizes the interests and broad focus areas of the IWG member agencies that have active efforts in or related to Manufacturing R&D for Hydrogen Technologies. Note that this table is not intended to describe projects in detail, but rather depicts the general areas in which the IWG member agencies are focusing their attention with respect to this technology area.

Table 2-1: IWG Agency Efforts in Manufacturing R&D for Hydrogen Technologies

IWG Agency	Interest Area / Focus
DOC / NIST	<ul style="list-style-type: none"> • NIST Laboratories are focused on measurements, standards, and infrastructure technologies required to assist the transition to high-volume manufacturing of hydrogen products • This includes advancing fundamental understanding of the role of fabrication, manufacturing metrology, and process control technologies critical to performance characteristics of fuel cells; using neutron imaging at the NIST Center for Neutron Research (NCNR) to address critical barriers in hydrogen production, storage, and utilization; developing new, quantitative methods for measuring properties of advanced materials proposed for hydrogen production, transportation, and storage systems; and developing physical measurement (reference) standards and calibration services for hydrogen flow-rate and purity.
DOD	<ul style="list-style-type: none"> • DOD is focused on fuel cell applications as alternatives to batteries, motors, and generators for warfighter and military vehicle/equipment applications. • The Defense Logistics Agency is operating a program to implement the use of fuel cell powered forklifts in Defense Depots, beginning in Susquehanna, PA. • Other military service-specific demonstrations are operating involving fuel cell powered vehicles in niche duty applications. These include applications involving the Army's National Automotive Center.
DOE	<ul style="list-style-type: none"> • DOE is the lead agency for the President's Hydrogen Fuel Initiative. Materials and technology development activities supported through this initiative are an ideal foundation upon which to build this manufacturing effort. The DOE strategy for addressing manufacturing is detailed in the draft <i>Roadmap on Manufacturing R&D for the Hydrogen Economy</i>. • The DOE Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science, and Technology; and Science are part of the Hydrogen Fuel Initiative. DOE's hydrogen-related programs are working with industry, university, and national laboratory partners to accelerate the development and successful market introduction of hydrogen production, delivery, storage, and fuel cell technologies.
DOT	<ul style="list-style-type: none"> • DOT is responsible for the regulatory oversight and is evaluating the risks and related requirements associated with the transport and storage of hydrogen materials, and their use in vehicular systems on our Nation's highways. DOT is focused on hydrogen safety technologies and safety education and training. DOT is also involved with the development and demonstration of heavy-duty vehicles and infrastructure.

Table 2-1: IWG Agency Efforts in Manufacturing R&D for Hydrogen Technologies (continued)

IWG Agency	Interest Area / Focus
NASA	<ul style="list-style-type: none"> • NASA is focused on several application areas where hydrogen and fuel cells are used in aerospace applications associated with space exploration and space shuttle operations. • NASA areas of interest include the manufacture, storage, delivery, and use of liquid hydrogen; polymer electrolyte membrane (PEM) fuel cells as possible replacements for alkaline fuel cell technology; advanced material development for hydrogen applications; solid oxide fuel cells for space applications; and hydrogen sensor technologies.
NSF	<ul style="list-style-type: none"> • NSF focuses on expanding the knowledge base and building capacity in particular areas by bringing to bear the research and education capabilities of the Nation's universities. • For manufacturing R&D for hydrogen technologies, NSF is interested in areas such as chemical and transport systems design, sensor networks, and advanced, comprehensive modeling at the component and plant levels.
USDA	<ul style="list-style-type: none"> • USDA areas of interest include hydrogen production and fuel-cell-based distributed energy production and compact storage systems. • For hydrogen production, R&D focuses on biomass gasification of agricultural plant residues, processing waste by-products, energy crops, and woody biomass; and microbiological processes using biomass and agricultural waste as feedstocks.

These agencies' participation in the IWG provides them the ability to coordinate current planning and future R&D efforts in a manner that leverages their separate efforts, results, and capabilities, as well as assures their alignment with an overall Federal strategy for addressing the challenges in hydrogen technology R&D. These agencies also participate in the NSTC's Interagency Working Group on Hydrogen and Fuel Cells (www.hydrogen.gov), which covers the full range of hydrogen-related research, development, and demonstration activities.

Research Challenges and Opportunities

U.S. industry has identified moving from today's laboratory-scale fabrication technologies to high-volume commercial manufacturing as a significant barrier to a future hydrogen infrastructure. Overcoming this barrier, as well as developing a domestic supplier base for hydrogen and fuel cell components, is the focus of the interagency manufacturing R&D effort being planned and coordinated by the IWG.

In addition, several national-level workshops have been held specifically to address issues associated with manufacturing R&D for hydrogen technologies — one in 2003 sponsored by NIST, another in 2005 sponsored by DOE, supported by NIST and the IWG.

The 2003 NIST workshop focused on strategies for high-volume manufacture of polymer electrolyte membrane (PEM)¹⁵ and solid oxide fuel cells. This workshop concluded that, "There is a need ... to better understand system interactions and to understand the effects of manufacturing process parameters and their variation on fuel cell system performance. ... Any fuel cell strategy would have to include working with other Federal and state government agencies, professional societies and fuel cell organizations, and the fuel cell and automotive industry."¹⁶

The July 2005 DOE workshop on Manufacturing R&D for the Hydrogen Economy, which included participation by industry and academia, identified three manufacturing technology areas for priority focus: (1) hydrogen production, (2) hydrogen storage, and (3) fuel cell systems. Based on discussions at that workshop¹⁷ the following sections and Tables 2-2, 2-3, and 2-4 summarize the priority challenges and needs in these three areas.

Hydrogen Production — Technology and Manufacturing Status

In 2003, approximately nine million tons (~9 billion kg) of hydrogen were produced annually, primarily for chemicals, petroleum refining, metals, and electronics.¹⁸ In the United States, nearly 95% of is produced via steam methane reforming; most of the remainder via water electrolysis. But hydrogen can be produced from a variety of energy resources, using a number of different process technologies.

In the near term, distributed production of hydrogen appears to be the most viable approach for introducing hydrogen and beginning to build a hydrogen infrastructure. In the longer term, large centralized hydrogen production facilities and their corresponding delivery systems that can take advantage of economies of scale will be used to meet increased hydrogen demand. Power options for high-volume hydrogen production include coal gasification with carbon sequestration, biomass gasification, and nuclear energy. Further down the

¹⁵ Also referred to as proton exchange membrane (PEM) fuel cells.

¹⁶ Center for Automotive Research (CAR), *Developing a National Strategy for High-Volume Manufacture of P.E.M. and Solid Oxide Fuel Cells Workshop*, a Report to the National Institute of Standards and Technology, February 2004, available at www.cargroup.org/publications.html.

¹⁷ U.S. Department of Energy, *Roadmap on Manufacturing R&D for the Hydrogen Economy*, draft released for public comment, 2005, http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf.

¹⁸ SRI Consulting, *Chemical Economics Handbook*, Menlo Park, CA: SRI, 2003.

road, successful R&D on photolytic technologies could lead to commercially viable systems that produce hydrogen directly from sunlight and water. Future possibilities also include manufacturing systems that will incorporate technologies using renewable energy sources such as wind, solar energy, and biomass. Each of these production processes has its own set of manufacturing requirements and challenges.

Production of hydrogen is capital intensive today. The smaller the facility, the greater is capital's share of the hydrogen cost. Capital's hydrogen cost contribution is 21% for a large 330,000 kg/day plant, rising to 52% for a 3,800 kg/day facility.¹⁹ The latter example estimates the capacity of a hydrogen fueling station serving 300 vehicles per day.²⁰ Much of the higher capital cost for smaller hydrogen production facilities of the type intended for distributed applications results from site-specific fabrication of fuel processing systems, which include reformers, shift catalyst beds, and pressure swing adsorption clean-up subsystems.

Standardization of design has not been established for hydrogen production facilities. In turn, design for manufacture has not been applied to foster standardization of

the subsystems. Fabrication of reformers and hydrogen purification systems based on site-specific requirements does not afford manufacturing cost reductions associated with volume. In part as a consequence of these factors, the Nation lacks the capacity for producing small-scale systems for distributed reforming of natural gas in quantities sufficient to help initiate the transition to widespread use of hydrogen technologies. To address this situation, the IWG has identified R&D priorities (see Table 2-2) that will help enable cost-effective manufacturing of distributed hydrogen production systems.

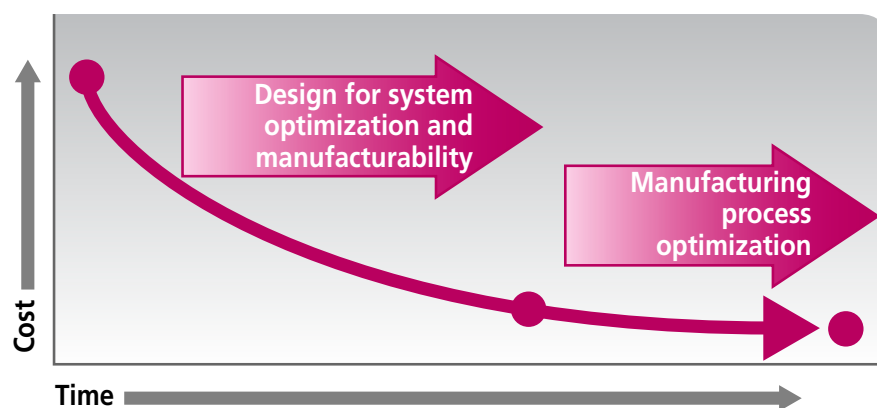


Figure 2-1: Cost Reduction approaches for hydrogen production

The cost of hydrogen production (and delivery) must be reduced substantially before it can be competitive with gasoline. Reducing cost while satisfying safety requirements necessitates revolutionary advances in production capabilities, realized in the form of affordable manufacturing systems. Figure 2-1 shows potential approaches to reducing manufacturing costs.

¹⁹ "Direct Hydrogen Fueled Proton Exchange Membrane Fuel Cell System for Transportation Applications," Hydrogen Infrastructure Report, Contract No. DE-IC02-94CD50389.

²⁰ Basis: 15 gallons per fill-up; 0.9 kg hydrogen is a gallon of gasoline energy equivalent.

Table 2-2: Manufacturing R&D Challenges for Distributed Hydrogen Production

Challenge	Description
Develop joining methods to facilitate component integration	Component integration requires labor-intensive welding. Manufacturers need high-reliability, low-variability joining processes that can be rapidly and robotically processed, are applicable to dissimilar material combinations, and enable leak-free hydrogen systems.
Develop metal joining methods that do not require high temperatures	Catalysts are being applied to reformer and electrolyzer components before the components are joined. High-temperature joining processes can damage the catalysts or make them inactive. Manufacturers will need low-temperature joining processes (e.g., laser or friction welding) that do not damage the catalyst coatings on the parts that are being joined.
Deposit catalyst coating onto nonconformal surfaces	A standardized, automated method for applying catalyst coatings to nonconformal surfaces (applying catalysts directly to heat exchange surfaces) will accelerate our ability to produce reformers and shift catalysts on a large scale. This approach will also benefit the deposition of catalysts onto electrode substrates for electrolysis. In-line quality control methods need to be developed.
Manufacture reactor vessels with protective coatings	Manufacturers will need an improved method for applying nickel cladding to lower the cost of metal substrates and to reduce overall material costs. Developing alloys for brazing that enable a corrosion-resistant reactor will be important.
Fabricate and heat-treat large-scale pressurized hydrogen vessels (for off-board storage)	The necessary retention of mechanical strength for pressure vessels is complicated by the thick walls needed for hydrogen containment. Advances in heat treatment of thick-walled vessels will lead to lower cost production processes. Laser heat treatment offers the opportunity for in-line processing of vessels.
Perform R&D for the manufacture of large composite pressure vessels using filaments (for off-board storage)	Filament-wound, composite pressure tanks are presently produced using “hand lay-up” techniques. Improved manufacturing methods for metallic, composite, and polymeric tanks are needed to resolve the issues of large-scale pressurized hydrogen storage (e.g., improved annealing methods and localized winding of carbon filaments).
Develop accelerated test methodologies to validate materials and processes	Accelerated test methods are needed to rapidly characterize performance in manufacturing processes and in end-use (product) applications.

Hydrogen Storage — Technology and Manufacturing Status

Today, hydrogen is stored aboard vehicles in tanks as either compressed gas or as a cryogenic liquid. Research is being conducted to develop solid-state and chemical hydrogen storage systems. These latter systems are already in early development stages. Limited supplies of tanks for storing compressed hydrogen at 5,000 pounds per square inch (psi) are now being manufactured in pilot-plant production procedures. Still under development are 10,000 psi tanks. Such storage vessels are typically carbon-fiber based. The manufacture of these tanks requires precise winding of the fibers over a mandrel that assures controlled alignment and spacing of the fibers, increasing the cost of the pressure vessel. Infiltration and curing of the epoxy filler is time consuming, but it is critical to eliminate flaws in the pressure vessel and ensure safety during use. Recent reports suggest that low-cost fibers and an optimal winding technology may bring down costs. Nonetheless, fiber winding and processing remain labor-intensive.

Laboratory and pilot plant production methods currently in practice may not be suitable for large-scale production of composite tanks. Laboratory efforts typically focus on resolving technical performance issues; the scale-up of laboratory production methods to full-scale mass production does not entail simply increasing all aspects of the laboratory process by a multiplicative factor. Present manufacturing of composites addresses high-value-added products such as aerospace components and high-performance sports equipment. Current manufacturing methodologies do not address mass production of components on the scale needed to make the transition to widespread hydrogen use. Little technical infrastructure is in place to enable this transition. There is a particularly acute need for the requisite metrology platforms to control high-volume manufacturing processes and systems.

In addition, current processes for manufacturing hydrogen pressure regulators and sensors add to the cost of the pressure vessels. While development efforts show progress in the integration of sensors (strain gauges) into the vessel shell, fabrication processes have not been optimized or validated for high-volume or large-batch production.

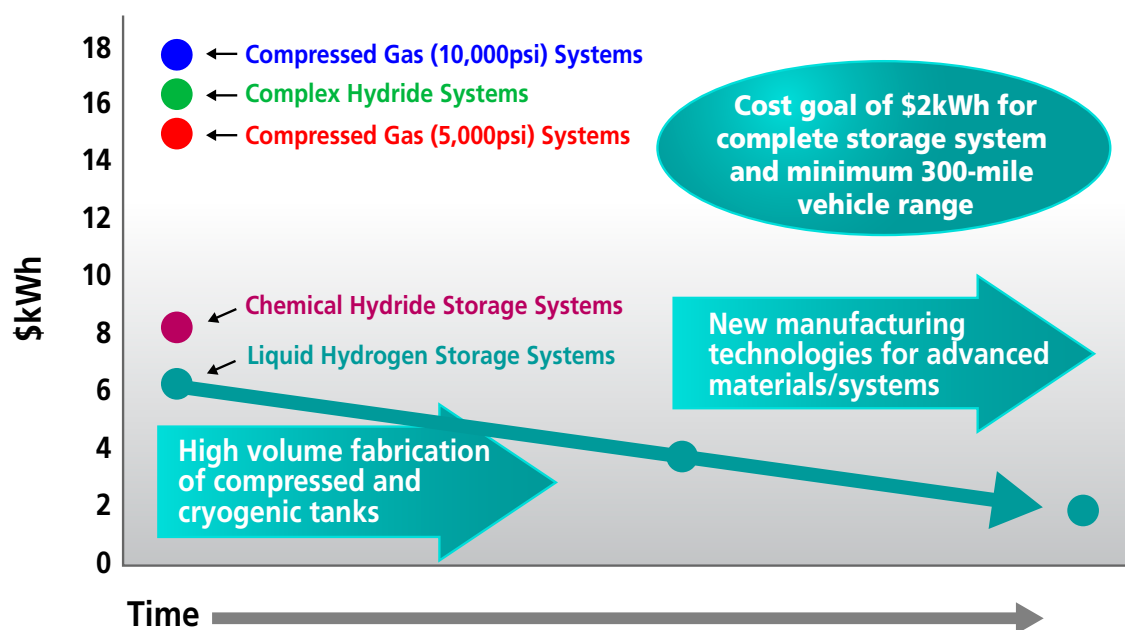


Figure 2-2: Pathway to reducing hydrogen storage cost: Combination of technology development and manufacturing R&D.

In the near term, compressed gas and liquid hydrogen tanks offer the best approaches for storing hydrogen. However, successful commercialization of hydrogen systems will likely depend on the development of materials like metal hydrides or chemical hydrides that can store hydrogen (for example, within their structure, on their surfaces, or as chemical compounds) at higher capacity and lower pressure than what is possible today. Research includes development of nanostructured materials for hydrogen storage, enabling synergy with nanomanufacturing initiatives. Development of improved high-volume manufacturing processes will play a role in reducing the current cost of hydrogen storage systems to meet the DOE target of \$2/kWh (approximately \$300 for a 5 kg hydrogen system). Figure 2-2 summarizes the pathway to cost reduction for hydrogen storage.

Cost targets for storage systems for compressed gas stored at 5,000 psi and 10,000 psi can be achieved by lowering the cost of carbon fibers through materials development and through moving to higher-volume manufacturing processes enabled by progress in manufacturing R&D (lower-left arrow in Figure 2-2).

Cost reduction for liquid hydrogen storage systems also can be achieved through materials development coupled to complementary manufacturing R&D efforts. Complex metal hydrides and chemical hydrides for materials storage applications are long-term technology pathways. Table 2-3 summarizes the R&D challenges for hydrogen storage.

**Table 2-3: Manufacturing R&D Challenges
for Hydrogen Storage**

Challenge	Description
Develop process technologies for reducing the cost of carbon fiber	Currently, composite tanks require high-strength fiber made from carbon-fiber-grade polyacrylonitrile precursor. The price of the carbon fiber is typically about \$20/kg. Reducing the cost of the fiber by about 30%, or about \$6/kg, would yield significant savings in the unit cost of composite tanks. Manufacturing R&D is needed to develop lower-cost, lower-energy decomposition process for carbon fibers, such as microwave or plasma processing.
Develop new manufacturing methods for high-pressure composite tanks	New manufacturing methods are needed that can speed up the cycle time, that is, the per-unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, and continuous versus batch processing (e.g., pultrusion processes). New manufacturing processes for applying the resin matrix, including towpregs for room-temperature curing, wet winding processes, and fiber-embedded thermoplastics for hot wet winding, should also be investigated.
Develop manufacturing technologies for high-pressure storage systems	Although this is a design issue (improved energy density), new manufacturing methods for carbon-fiber winding and fiber placement manufacturing could also be applied to improve tanks by allowing modified cylindrical tank shapes to be manufactured.
Improve fiber placement processes	Improved fiber placement technologies can reduce unit costs by reducing the amount of fiber needed by as much as 20–30%. This approach may also allow some improvement in conformability of high-pressure tanks. However, the process is slow. New methods and equipment are needed to improve manufacturing cycle time.

Hydrogen Utilization: Fuel Cells — Technology and Manufacturing Status

Individual fuel cells (and size-scalable fuel cell “stacks”) are now manufactured using laboratory fabrication methods that have been scaled-up in size but do not incorporate high-volume manufacturing methods. As an example, for fuel cells based on PEM technology, the fabrication of the membrane electrode assembly (MEA) — a five-layer structure — is typically accomplished in five separate stages. The multilayer structure is then hot-pressed to bond the layers together. The final product is called, depending on the manufacturer, a unified electrode assembly or unified cell device, UCD. All of these fabrication steps are conducted as discrete operations, with most of the actual labor done by hand; indexing the anode and cathode layers, in particular, is time-intensive.

Precious metal catalysts contribute significantly to the overall cost of fuel cells. Recognized, reliable, repeatable measurement technologies and methods that allow catalyst application within fuel cell stacks to be optimized would lead to reduced cost, from both a materials and process perspective.

Status of Fuel Cell Manufacturing

Fuel cell manufacturing is a labor-intensive process requiring hand lay-up of the membrane-electrode assemblies and labor-intensive assembly of fuel cell components. Most processes for the manufacture of fuel cells are modifications and expansions of laboratory procedures.



Assembly of the fuel cell stack requires exacting control of the layout of the individual UCDs to ensure direct alignment of the electrodes in adjacent cells. Between the UCDs is the bipolar plate, in which flow fields are carefully indexed. For cells with internal manifolds, sealing of the bipolar plate to the UCDs is critical to avoid mixing of reactant gases. An additional component for the stack is the cooler plate, which — like the bipolar plate — must maintain strict flatness and parallelism tolerances. Assembly today requires repetitive measurement of stack components and meeting close tolerances for seal connections to assure that quality and performance are maintained. Manufacturing of ancillary equipment, such as compressors, flow controllers, and converters, also must be addressed.

As fuel cell manufacturing scales up, it is imperative that the relationships between fuel cell system performance and manufacturing process parameters and variability be well understood. Such understanding does not currently exist on a broad basis but can play a major role in fuel cell design, tolerances, and specifications. It is integral to the implementation of design for manufacturability. Modeling and simulation can play a significant role in developing this knowledge.

In addition, a large-scale shift from gasoline to hydrogen-powered vehicles will potentially require a global shift in material consumption. For example, increased consumption of platinum for fuel cells may have economic and environmental implications. Understanding these potential implications early on will enable the U.S. government and manufacturing industry to be proactive rather than reactive.

Major fuel cell subsystem components, such as the air delivery system and the cooling system, are individually assembled and then joined to other components. Heat exchangers must be connected to the coolant system, for example, and the humidification system must be integrated with the air blower. Construction of the power plant is usually done through the integration of subsystems; however, each subsystem is typically assembled separately in a labor-intensive process. Gas, water, and coolant manifolds are constructed on-site. Each connector must be separately cut, prepared, and joined to the subsystem. Prefabrication of components and the molding of components are limited. A lack of standardization of components is one reason for limited manufacturing capability.

Today the high-volume production cost estimate of fuel cells is about four times the DOE target of \$30/kW. Figure 2-3 illustrates the pathway to cost reduction of PEM fuel cells.

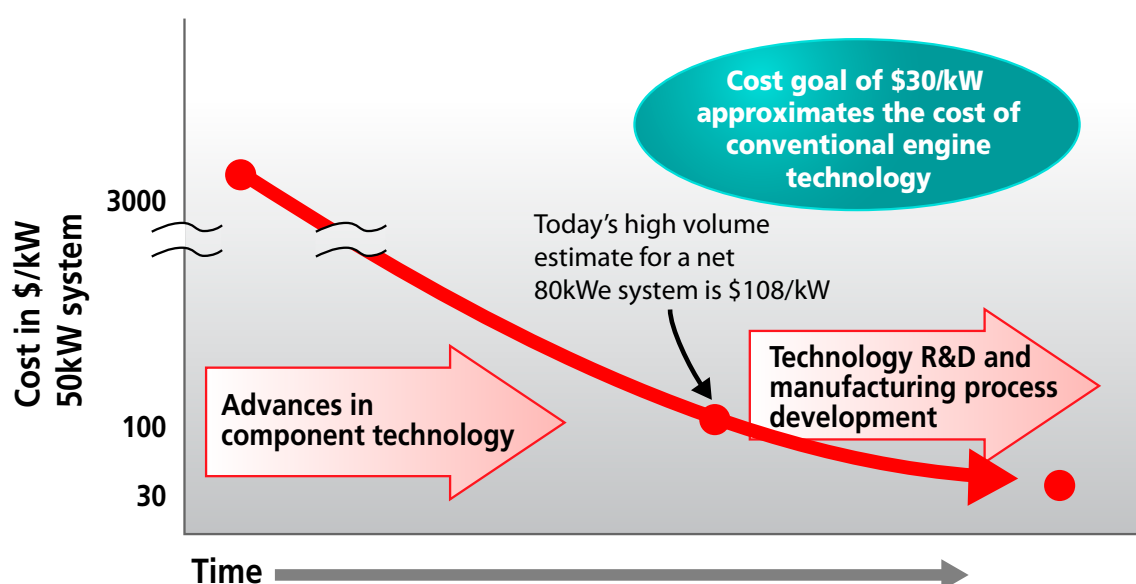


Figure 2-3: Pathway to reducing the cost of PEM fuel cells: Combination of technology development and manufacturing R&D.

Today's estimated cost of fuel cells using current technology with high-volume manufacturing is based upon advances already achieved in MEA technologies (as well as advances in other fuel cell components) and coupled to assumptions of high-volume manufacturing. This will require R&D to develop the necessary processes. As described in Table 2-4, further cost reduction will require R&D both on fuel cell technologies and new manufacturing processes.

Cross-Cutting Research Opportunities

The manufacture of components and systems for the hydrogen fuel cells requires a wide spectrum of technologies, from continuous chemical processes to discrete mechanical fabrication processes. Diverse issues and challenges are associated with each of these manufacturing processes. However, significant cross-cutting manufacturing technology requirements span the three broad categories of hydrogen production and delivery, hydrogen storage, and hydrogen utilization through fuel cell systems: Improved manufacturing processes to achieve cost reduction targets.

- High-speed manufacturing processes to meet the production volumes that are required to transition to and sustain the widespread use of hydrogen technologies
- Accurate, reliable, and measurable manufacturing processes to achieve the necessary quality levels, which affect performance, reliability, durability, and safety

These issues are identified in more depth in the 2005 draft *Roadmap on Manufacturing R&D for the Hydrogen Economy*.

Table 2-4: Manufacturing R&D Challenges for PEM Fuel Cells

Challenge	Description
Identify relationships between physical and manufacturing properties of MEAs and performance properties of MEAs	Manufacturing R&D that correlates physical properties of the MEA with performance properties is a high-priority need. The relationship needs to be established between the ex situ manufacturing properties and the in situ properties that pertain to performance and durability. The relationship could be an empirical-, mathematical-, or physical-based transfer function. Supporting this approach is a strong need for sensor technology that would permit in-line inspection and would provide the database for statistical quality control.
Identify cost of PEM fuel cells, especially MEAs, at several levels of manufacturing volume	Industry considers characterizing a continuum in the development of fuel cells, especially the MEA, to be an important issue. A broad range of cost analyses is needed that embrace the transition from low production levels to high production levels in order to establish progress goals in the development of manufacturing processes.
Develop agile, flexible manufacturing	Changes in manufacturing in response to changes in the materials and designs of MEAs result in high costs. More flexible (agile) and integrated manufacturing approaches are a high priority for the manufacture and assembly of MEAs. Industry will need agile manufacturing processes that can be adapted to developing membrane, catalyst, and gas diffusion layers without incurring major capital expenditures.
Develop understanding of how manufacturing parameters affect catalyst layers	The relationship between catalyst layer fabrication and the performance and durability of the resultant catalyst layer needs to be delineated to implement high-speed manufacturing processes. New methods of manufacturing will be important to fabricate new catalyst layers that meet the low precious metal cost-loading targets.
Develop strategies for high-speed seal applications	High-speed processes need to be developed to integrate MEA components by incorporating edge and interfacial seals and gaskets. Merging the MEA sealing assembly process with the bipolar plate sealing in a continuous process could lead to cost reductions in the assembly of the cell stack.
Apply and develop modeling tools for MEA manufacture	Integration of computer-aided design tools with technology development and manufacturing R&D will enable improved performance and reduced cost.

Table 2-4: Manufacturing R&D Challenges for PEM Fuel Cells (continued)

Challenge	Description
Characterize membrane defects and develop fabrication techniques	It is important to characterize defects in membranes and their causes to permit in-line control of membrane and MEA manufacture.
Develop high-speed forming, stamping, and molding of bipolar plates	Current processes individually form or machine the bipolar plates. Manufacturing bipolar plates requires the development of new high-speed forming, stamping, and molding processes that will maintain the high tolerance requirement of the PEM fuel cell. Rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates is on the critical development path.
Develop automated processes to assemble cell stacks	Automated processes are needed to rapidly assemble cell stacks. Design for manufacturability and assembly should be applied to cell stack development to enable processes that lead to identical cells and eliminate the need to measure each cell component during cell stack assembly.
Develop high-speed welding/joining	Present laser welding methods are either too slow or too expensive for metallic bipolar plate manufacturing. Techniques for microwelding bipolar plates need to be developed to achieve linear welding speeds greater than 50 meters per minute.
Develop materials for low-cost, high-performance heat exchangers (materials issue)	PEM fuel cells have at least four heat exchangers within the balance of plant (BOP). Composite or plastic heat exchangers that can be fabricated at high volume and low cost could provide a low-cost path for the manufacture of PEM power systems. Manufacturing processes will need to be developed for these new materials.
Establish protocols for qualifying new materials and processes (materials issue)	Materials that are compatible with PEM fuel cells need to be identified for all manufacturers. Currently, individual fuel cell manufacturers specify acceptable materials. A compilation of materials acceptable to all fuel cell manufacturers will enhance establishment of a supplier network. Protocols need to be developed for qualifying new materials to be used in the manufacture of PEM fuel cells.

Table 2-4: Manufacturing R&D Challenges for PEM Fuel Cells (continued)

Challenge	Description
Develop frameless fuel cell systems (design issue)	PEM power systems are currently built by fitting components and subsystems in the power system box. Improved designs for assembly of the unit would address the interaction of subsystems and enable advanced concepts for production and assembly of power systems. Design for manufacturing and assembly should be applied to the BOP to reduce the part count of integrated systems.
Develop manufacturing and assembly processes for interim production volumes	Manufacturing approaches suitable for an interim production volume of 5,000–50,000 power systems per year are a pathway to large-scale transportation production processes. Rapid prototyping and agile manufacturing will be important pathways for the construction of fuel cell balance of plant and PEM power systems.
Establish a technology facility for flexible automated manufacturing	A national facility is needed to test flexible, automated manufacturing technology for BOP and power system assembly and component manufacture. It could provide a testbed for developing manufacturing processes, could be available to component and fuel cell manufacturers, and could serve as a clearinghouse for PEM fuel cell manufacturing R&D.
Develop production hardware for rapid leak detection	Leak testing of the BOP and power system is time-consuming and costly for today's PEM fuel cell power system production. Rapid leak testing is needed that can be accomplished in the production line and at production line rates.

Recommendations and Next Steps for the IWG

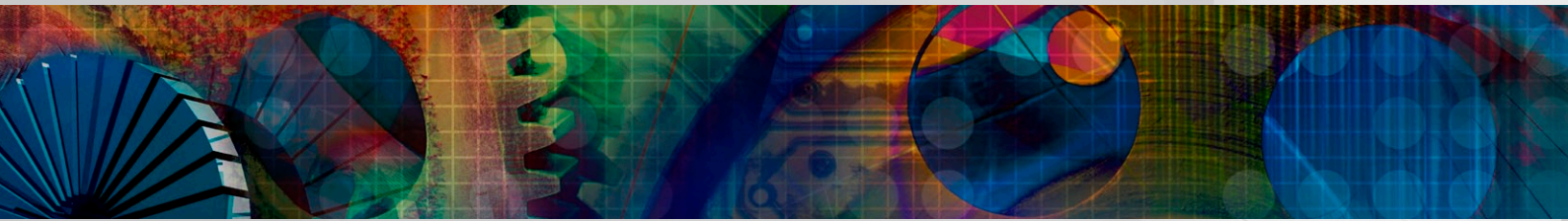
Manufacturing R&D activities must be conducted synergistically with materials and technology development activities supported through the President's Hydrogen Fuel Initiative. Such integration is critical to success of the Initiative and to ensuring the vitality of the manufacturing sector during and after the transition to hydrogen. To this end, the President's FY 2007 and 2008 Budgets for the Department of Energy have included funding for a sustained, multiyear effort on manufacturing R&D for hydrogen technologies. DOD released R&D solicitations in this area in 2006 and 2007.

The IWG is working to coordinate agency activities to ensure Federal R&D targets the right issues. Ultimately, the development of the manufacturing infrastructure needed to effect and sustain the Nation's transition to the widespread use of hydrogen technologies is critical. Through its member agencies, the IWG will coordinate the following:

- Continued development of the manufacturing R&D roadmap, together with industry and academia, to lay out a strategy for guiding future Federal involvement in this area. The draft *Roadmap on Manufacturing R&D for the Hydrogen Economy* resulting from the DOE Workshop on Manufacturing R&D for the Hydrogen Economy lays the foundation for future interagency efforts in this area.
- Planning of technical workshops on an as-needed basis to continue to engage the industrial and academic communities to ensure awareness of industry's most pressing manufacturing needs and challenges in this area.
- Efforts to catalyze and contribute to the development of industry-led manufacturing standards necessary for transition to the widespread use of hydrogen technologies.

Chapter 3

Nanomanufacturing: Fulfilling the Promise of Nanotechnology



Definition and Scope

The IWG defines nanomanufacturing as all manufacturing activities that collectively support practical approaches to designing, producing, controlling, modifying, manipulating, and assembling nanoscale elements or features for the purpose of realizing products or systems that exploit properties seen at the nanoscale.

Nanotechnology is the science, engineering, and technology related to the understanding and control of matter at the length scale of approximately 1 to 100 nanometers. Novel characteristics of matter at the nanoscale offer the promise of significant innovation across a spectrum of products that will affect virtually every industrial sector and, at the same time, enhance the health, security, and wealth of the Nation.

Nanomanufacturing is the vehicle by which the Nation will realize the benefits of nanotechnology. These benefits will result through enhanced performance of products in a wide range of industries that include aerospace, automotive, communications, energy, environmental remediation, information, medical, pharmaceutical, and power. At the same time, realizing the promise of nanotechnology through the development of practical manufacturing methods will likely lead to industries and products yet to be imagined.

Basic Research

Nanomanufacturing enterprises of the future will transform knowledge and materials into products and systems valued by society. Before commercialization can be achieved, however, important science and technology challenges must be addressed. Research will be required to obtain the knowledge and develop processes and tools needed to make the transformation to products and systems. Profitability goals demand predictability of product performances and lifecycles, as well as of the nanomanufacturing enterprise, its processes, systems, and supply and distribution chains.

Nanomanufacturing is widely recognized as an exciting high-tech area where U.S. manufacturers have an opportunity to take a global leadership role in setting the stage for a number of fundamentally new materials, processes, and products. Nanotechnology presents many opportunities for sustaining the Nation's manufacturing competitiveness over the long term.

Tools for Nanomanufacturing

Current materials research on nanoscale elements (nanoparticles, nanotubes, fullerenes, nanostructured materials, nanocomposites, etc.) requires concurrent manufacturing research efforts on the development of processes and tools. One approach to nanomanufacturing research is to use the nanoscience tools of today such as the scanning-tunneling microscope or the atomic force microscope to help generate ideas and create the tools that will underlie the development of an industry. A second approach is to design tools specific to nanomanufacturing that utilize new approaches to sense and manipulate at the nanoscale.

Societal Issues Beyond Technology

Advances in understanding of processes and materials at the nanoscale will lead to new technologies that may have widespread societal implications. These implications should be considered in parallel with R&D efforts focused on nanoscale science and technology:

- What will new nanomanufacturing enterprises look like, and what steps are needed to create them? What new industries will result?
- What impact will these new processes, systems, and industries have on our current industrial base?

- What will be the skill sets required for a technically literate workforce and the corresponding infrastructure for education?
- What will be the size of a typical nanomanufacturing enterprise, and how will such enterprises be distributed?
- Will products be high-volume, low-value; or low-volume, high-value; or a mix; and will the new industries be transformative?
- What are the potential environmental implications of nanotechnology and nanomanufacturing, and how might those implications affect investment?
- With the potential creation of new industries, what economic, health, safety, national security, and sustainability issues should be anticipated — and what proactive measures should be taken to address those issues?
- And, ultimately, what will be the benefits of creating the new industries and how can those anticipated benefits be optimized?

Federal R&D and Coordination Efforts

The IWG aims to help maintain a sharp focus on manufacturing technology within a broad range of existing and developing Federal research endeavors related to nanotechnology challenges and opportunities. Broadly speaking, these Federal endeavors are aimed at enabling the scaled-up, reliable, cost-effective design and manufacture of nanomaterials, nanostructures, nanodevices, and nanosystems. Many of these efforts have been focused on meeting agency-specific needs. However, since its establishment in 2001, there has been a strong effort at coordinating these activities under the auspices of the National Nanotechnology Initiative (NNI), led by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC, with the administrative and technical support of the National Nanotechnology Coordinating Office (NNCO). NNI goals are to maintain a world-class R&D program aimed at realizing the full potential of nanotechnology to benefit society. The IWG is coordinating its efforts with those of the NSET Subcommittee.

NNI Nanomanufacturing Efforts

A key function of the NNI has been to prioritize Federal R&D investments related to nanotechnology R&D. An early step in that process has been to define Program Component Areas (PCAs) that describe key areas of investment critical to accomplishing the goals of the NNI. The scope of the nanomanufacturing PCA is outlined in the sidebar.

NNI-supported nanomanufacturing R&D activities are reported in the annual supplements to the President's NNI budget requests and in a 2007 NNI report titled, "Manufacturing at the Nanoscale," specifically focused on nanomanufacturing.²¹

Focus of the NNI Nanomanufacturing Program Component Area

Nanomanufacturing R&D is aimed at enabling scaled-up, reliable, cost effective manufacturing of nanoscale materials, structures, devices, and systems. This includes R&D and integration of ultra-miniaturized top-down processes and increasingly complex bottom-up or self-assembly processes.

-From the NNI website <http://nano.gov>

Nanomanufacturing is taken to include all means that have the capability to reproducibly transform matter — from a bulk form or from individual atoms, molecules, and supramolecular structures — into nanoscale or nanostructured materials, devices, or systems with desired properties and performance characteristics, typically in large quantities.

-From the NNI Supplement to the President's 2007 Budget

The NNI agencies that have requested Federal funding for R&D relating to nanomanufacturing are DHHS/NIH, DOC/NIST, DOD, NASA, NSF, and USDA; other NNI agencies with an interest in nanomanufacturing include DOE, DOT, and EPA. Each of these NNI agencies is also a member of the IWG. The NNI supplements to the President's FY 2006, 2007, and 2008 budgets identify these agencies' strategic R&D priorities related to the Nanomanufacturing PCA:

Each of these NNI agencies is also a member of the IWG. The NNI supplements to the President's FY 2006, 2007, and 2008 budgets identify these agencies' strategic R&D priorities related to the Nanomanufacturing PCA:

- Research into use of self-assembly, directed self-assembly, programmed self-assembly, biologically driven self-assembly, and scanning-probe-based techniques for control of matter at the nanoscale (including biologically inspired processes and techniques), and into methods for integrating manufactured nanoscale products into larger application structures

- Development of process control and quality control in manufacturing at the nanoscale based on traceable metrology

²¹ National Science and Technology Council (NSTC) Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee (NSET). Relevant documents may be found on the NNI website's publications page, <http://nano.gov/html/res/pubs.html>. "Manufacturing at the Nanoscale" is available at www.nano.gov/NNI_Manufacturing_at_the_Nanoscale.pdf.

- R&D on precompetitive nanomanufacturing problems such as scale-up and reproducibility of nanomanufacturing processes
- Establishment of one or more centers focused on nanomanufacturing research, via collaborative efforts among existing Federal agencies, programs, and offices with interests in manufacturing
- NNI coordination with other Federal efforts to enhance the U.S. manufacturing infrastructure, providing jobs and other economic benefits
- Efforts to seek and utilize advice from the electronics, chemical, and other industries to sharpen the Federal program.
- Development of manufacturing processes that incorporate nontoxic constituents and that use less energy, water, and other resources

Two of the NNI nanomanufacturing priority areas — those relating to the development of manufacturing process and quality control based on metrology and instrumentation R&D, as well as the establishment of research centers focused on nanomanufacturing — represent areas of particular interest to the IWG and are further articulated below.

Metrology and Instrumentation R&D

As noted earlier in this report, instrumentation and metrology are vital aspects of manufacturing, and it will be important that the nanomanufacturing R&D community will work closely with the instrumentation and metrology community. Instrumentation research, metrology, and standards for nanotechnology is also an NNI PCA, which is intended to promote R&D pertaining to the tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. The NNI instrumentation, metrology, and standards PCA includes R&D and other activities related to development of standards, including standards for nomenclature, materials, characterization and testing, and manufacture.

The NNI Instrumentation and Metrology Grand Challenge Workshop held in January 2004 was structured to include a nanomanufacturing session.²² And in October 2006, the IWG organized a conference focused specifically on Instrumentation, Metrology, and Standards for Nanotechnology that was sponsored by NIST, NSF, and the Office of Naval Research. At these and other workshops, it has been clear that there is strong interagency support for the development of a metrology infrastructure for nanotechnology, especially with respect to establishing standards and to supporting successful commercialization of R&D. The IWG plans to build on the NNI foundation work in this area by further articulating relevant nanomanufacturing-related needs and challenges. Details of these IWG plans are contained in the Recommendations section of this chapter.

Infrastructure: Centers and User Facilities

The NNI has recognized the need to establish user facilities that make often costly, state-of-the-art instrumentation available to all researchers. In addition, to supporting large-scale, multidisciplinary research, including for nanomanufacturing, the NNI has funded a number of research centers. The resulting infrastructure is geographically distributed and, in the case of user facilities, available to the broad research community. The nanomanufacturing-related research center and user facility activities at three of the IWG agencies are described below.

NIST Center for Nanoscale Science and Technology (CNST).

The developing CNST at NIST is designed to address need of the Federal government and industry for a wide range of nanoscale measurements and instrumentation. CNST has a primary goal of enabling the manufacture of products incorporating nanotechnology. It will work closely with industry, academia, and other government agencies to provide essential measurement methods, instrumentation, and standards to support all phases of nanotechnology development, from discovery to production. CNST's twin focus on measurement and processing at the nanoscale make the center an important addition to the Nation's nanotechnology infrastructure.

CNST operates at the NIST Advanced Measurement Laboratory (AML), which is one of the most technologically advanced buildings in the world, providing NIST researchers the environment necessary to effectively respond to the industry's need for standards and measurements key to

²² NSET Subcommittee, Committee on Technology of the NSTC, *Instrumentation and Metrology for Nanotechnology: Report of the NNI Workshop*, January 2004, available from the National Nanotechnology Coordination Office or by download from <http://www.nano.gov>.

realizing nanoscale products. The AML allows scientists and engineers to achieve strict temperature and humidity control, vibration isolation, air cleanliness, and quality of electric power. Freed from disruptive environmental influences, NIST scientists and engineers will develop tools and methods that will permit laboratory accomplishments to progress to the level of practical applications.

DOE Nanoscale Science Research Centers (NSRCs). NSRCs moving into operations at DOE National Laboratories offer a unique opportunity to couple synthesis capabilities with world-leading characterization equipment to address challenges in understanding materials chemistry, materials behavior, and materials performance. The NSRCs operate as national user facilities, with access based on peer review of proposals. These facilities also have leading groups in a number of areas relevant to *ab initio* and atomistic modeling coupled with cutting edge computational facilities. The possibility of developing technology platforms for nanomanufacturing in these centers — consisting, for example, of standardized chip sets for testing, or of reproducible and comparable materials deposition and patterning protocols — presents an opportunity for comparative and precompetitive work on nanomanufacturing in a number of areas. The locations of these facilities offer geographically distributed capabilities for the scientific and engineering communities to interface with industry and assist in solving difficult problems in process research, process design, and process modeling.

NSF National Nanomanufacturing Network (NNN). The NNN is a community-driven open access network that facilitates collaboration and disseminates information among the nanomanufacturing research, education and development community. This network is designed to be a catalyst for the advancement of new approaches in nanomanufacturing in the U.S. The NNN is funded by NSF, as part of the NNI, through a grant to the University of Massachusetts. The NNN will provide connections to nanomanufacturing centers, projects and experts from academic, industrial and government institutions. The NNN plans to offer a network of expertise and technologies, thematic workshops on emergent nanomanufacturing methods, educational opportunities in nanomanufacturing and a web-based nanomanufacturing information clearinghouse. The NNN clearinghouse will provide information on nanomanufacturing centers, experts and resources, nanomanufacturing processes, nanostructured materials, best practices, events, and a database of nanomanufacturing research information. The NNN is funded and coordinated by stakeholders from NSF, NIST, DOD, DOE, NIH, NIOSH and many other institutions.

NSF Nanoscale Science and Engineering Centers (NSECs).

NSECs address opportunities that are too complex and multifaceted for individuals or small groups of researchers to tackle on their own. The centers bring together researchers with diverse expertise, in partnership with other private and public sector organizations, to address complex, interdisciplinary challenges. They integrate research with education both internally and through a variety of partnership activities. Each NSEC, whether based at a single institution or distributed across a number of institutions, has an overarching research and education theme, well-integrated programs, and a coherent and effective management plan. The NSECs as a whole span the range from exploratory research — focused on discovery — to technology innovation, and involve a broad spectrum of disciplines such as engineering, mathematics and computer science, the physical, biological, environmental, social, and behavioral sciences, and fields in the humanities.

A key component of each NSEC's mission is to develop a diverse U.S. workforce of educators, scientists, engineers, and practitioners to advance nanomanufacturing technology in the United States and globally. The centers' education programs are designed to develop an innovative and diverse workforce, advance precollege training, address societal implications related to the research topic of each center, and to advance the public understanding of science and engineering. This includes a wide range of human resource development activities targeted toward increasing diversity of students involved with the center, providing educational opportunities at the K–12 and undergraduate levels, and providing

graduate students with unique research and teaching experience in this emerging field. The scope of individual NSECs and the disciplines involved vary, yet combined they provide a unique and powerful infrastructure to confront the formidable challenges that lay ahead.

The NSF NSECs that are founded on manufacturing at the nanoscale are managed by the Engineering Directorate. Additionally, NSF recently established the National Nanomanufacturing Network (NNN) that is led by the University of Massachusetts Amherst, and that will collaborate with researchers funded under DOD and NIST nanomanufacturing programs. The NSF nanomanufacturing NSECs embrace a vision for a new manufacturing paradigm that combines fundamental science and technology in nanomanufacturing to transform laboratory science and engineering into exciting new applications and industries. These centers are driven by a strong system focus that emphasizes manufacturability, scalability, and reliability and look to create the next generation of nanotools and systems that will enable cost-effective nanomanufacturing. Each center must also forge a new education platform for multidisciplinary science and engineering by integrating research and education in manufacturing. Through partnerships and collaborations among the nanomanufacturing centers and other NSECs, these common elements serve to strengthen the entire nanotechnology community and make possible products with undreamed of functionality that is enabled by nanotechnology.

Below is a brief description of the goals and focus of three nanomanufacturing NSECs.

- *UCLA Center for Scalable and Integrated NanoManufacturing (SINAM).* The UCLA SINAM is addressing several major challenges: to manufacture nanodevices below 20 nm, to fabricate 3D complex nanostructures, and to heterogeneously integrate multiple functionalities. SINAM set its goal to develop a new manufacturing paradigm that integrates an array of new nanomanufacturing technologies, including Plasmonic Imaging Lithography and Ultra-molding Imprint Lithography aiming toward critical resolution of 1-50 nm and the hybrid top-down and bottom-up technologies to achieve massively parallel integration of heterogeneous nanoscale components into higher-order structures and devices. The new manufacturing technologies developed at SINAM will open an exciting gateway to applications in computing, telecommunication, photonic, biotechnology and medicine. SINAM supports or engages scientists and engineers from six institutions: UCLA, UC Berkeley, Stanford University, UC San Diego, University of North Carolina, and Hewlett Packard Laboratories.
- *University of Illinois at Urbana-Champaign Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS).* The goal of the Nano-CEMMS research program is to create a viable manufacturing technology and science base that can fabricate ultrahigh-density, complex nanostructures. To achieve this goal the Center plans to develop a reliable, robust, and cost-effective nanomanufacturing system to make nanostructures from multiple materials. The Center is pursuing research in development of a micro-nano fluidic toolbit, nanoscale sensing devices and approaches, and manufacturing systems whose development is guided by a set of application focus areas in combinatorial chemistry, chemical/biological sensors, and electronics devices. The Nano-CEMMS Center members include scientists and engineers from three institutions: University of Illinois, the California Institute of Technology, and North Carolina Agricultural and Technological State University.
- *Northeastern University Center for High-Rate Nanomanufacturing.* The goal of the Northeastern Center for High-Rate Nanomanufacturing is to conduct research in areas that support high-volume, high-rate, integrated assembly of nanoelements into commercial products. In pursuit of this goal, the Center introduces novel science such as high-volume, room-temperature, uniform nanotube synthesis; fabrication of fullerene nanowires; and nanotemplates for guided self-assembly of nanoelements and patterning polymer blends at high rates. The effort also involves controlling position, orientation, and interconnectivity of the

nanoelements. The Center members include Northeastern University, the University of Massachusetts Lowell, the University of New Hampshire, Michigan State University, and the Boston Museum of Science.

- *University of Massachusetts Amherst Center for Hierarchical Manufacturing (CHM)*. The CHM's mission is to conduct leading research in nanotechnology and to foster the development of new advances from laboratory innovation to manufacturable components and devices. Hierarchical Manufacturing refers to the sequential process of fabricating functional nanostructures of specified size, morphology and composition, then integrating the nanostructures into device elements, and finally integrating the elements into systems and products. The CHM's research focus includes both tool and process development, and its research portfolio includes six enabling technology areas: (1) ordered arrays over large areas in block copolymers, (2) imprint lithography with new materials, (3) stable 3-D nanoporous structures, (4) block copolymer tissue engineering scaffolds, (5) functional surfaces, particles and device layers, and (6) nanoscale device design. The CHM is the latest example of a decade-long process of investment and achievement in nanotechnology research at

Massachusetts' flagship public research university. More than 50 faculty from eight departments at UMass Amherst conduct research on nanotechnology, coordinated through the MassNanoTech Institute campus-wide initiative.

IWG Coordination Efforts

The IWG efforts in nanomanufacturing complement the continuing nanomanufacturing efforts organized under the NNI. The IWG looks to align nanomanufacturing activities with other Federal manufacturing programs and to serve as a forum for joint program planning in nanomanufacturing. The IWG also draws upon enterprise-level manufacturing research and other advanced development expertise common to a broad array of manufacturing enterprises. This expertise ranges from supply chains to methods and tools to design integrated products, to the infrastructure to assure the producibility and predictability of nanoscale products, and the productivity of nanomanufacturing processes and enterprises.

In addition to the activities reported in the annual NNI budget supplements, the IWG collected information from its member agencies shortly after its formation in 2004 concerning their R&D activities relevant to nanomanufacturing. Information from these two sources is summarized in Table 3-1.

Table 3-1: Summary of Federal Nanomanufacturing R&D Efforts by Agency and Application Area

IWG Agency	Infrastructural Applications	Product/Process-Specific Applications
DHHS	<ul style="list-style-type: none"> • Environmental safety and health • Physical characterization and in-vitro assays of nanoparticles • Informatics tools for predicting biophysical properties and interactions; promote data sharing • Workforce education and training 	<ul style="list-style-type: none"> • Nanoscale diagnostic and therapeutic devices
DOC/NIST	<ul style="list-style-type: none"> • Measurements, standards, and data crucial to both private industry's development of nanotechnology-based products, as well as Federal agencies' efforts to exploit nanotechnology to further their missions, such as national security and environmental protection • Enable science and industry by providing essential measurement methods, instrumentation, and standards to support all phases of nanotechnology development, from discovery to production. 	
DOD		<ul style="list-style-type: none"> • Nanostructures for defense devices, systems, and materials • Material surface treatment and coatings
DOE	<ul style="list-style-type: none"> • Basic research on nanomaterials: synthesis and characterization 	<ul style="list-style-type: none"> • Possibility of developing technology platforms for manufacturing
DOL	<ul style="list-style-type: none"> • Workforce training and education 	

IWG Agency	Infrastructural Applications	Product/Process-Specific Applications
DOT		<ul style="list-style-type: none"> Nanomaterials for use in improved transportation infrastructure (roads, bridges, pipelines, etc.)
ED	<ul style="list-style-type: none"> Career awareness and preparation pathways aligned with employer and post-secondary validated curriculum standards. Career Pathways that provide rigorous programs of study to prepare students for careers in the Manufacturing and Science, Technology, Engineering, and Mathematics career clusters. 	
EPA	<ul style="list-style-type: none"> Ecological and human safety and health assessment Life Cycle Assessment 	<ul style="list-style-type: none"> Nanodevices for environmental treatment, remediation, and sensing Nanomaterials as substitutes for toxic materials Life cycle material and energy efficiency realized through nanotechnology
NASA		<ul style="list-style-type: none"> Miniaturized sensors for space exploration Lightweight, high-performance, multifunctional structures
NSF	<ul style="list-style-type: none"> Research on obstacles to high-rate production and nanomanufacturing reliability, robustness, yield, efficiency, and cost effectiveness Workforce training and education 	
USDA	<ul style="list-style-type: none"> Biologically based nanoscale manufacturing of materials and devices College-level education of nanobiotechnology relevant to agriculture and food systems 	<ul style="list-style-type: none"> Nanoscale detection of food pathogens and toxins Functionalize nanoparticles for food safety intervention Nanoscale delivery of nutraceuticals in foods

The IWG's 2004–2005 “snapshot” of Federal nanomanufacturing R&D indicates that member agencies are conducting a wide variety of activities that align with their respective missions, focusing on infrastructural applications as well as on process and product applications specific to agency needs. Within the scope of agency research efforts are tools, processes, and work to meet challenges in nanomanufacturing that include

- synthesis and processing of nanoelements or nanoscale building blocks (nanotubes, nanoparticles, nanofibers, and quantum dots)
- nanotube dispersion in nanocomposites and atomic-layer deposition for nanoelectronics
- patterning and templating of polymeric and biomolecular systems
- directed assembly of 2D and 3D structures and devices
- positioning, imaging, and measurement at nanoscale resolution
- modeling and simulation of material-energy interactions and manufacturing processes at the nano-, micro-, meso-, and macro-scales

Research Challenges and Opportunities

Nanomanufacturing R&D integrates science and engineering knowledge and develops new processes and systems to assure quality nanomaterials, to control the assembly of molecular-scale elements, and to predictably incorporate nanoscale elements into nano-, micro-, and macroscale products utilizing new design methods and tools.

Anticipated R&D Phases

Systematic control and manufacture at the nanoscale are envisioned to evolve in four overlapping generations of new nanotechnology product types that start with nanoscale building blocks and evolve through complex heterogeneous systems.²³ Each anticipated generation of products will provide a nanotechnology base for further innovation, leading to succeeding generations of products of increasing complexity and functionality:

- **First Generation** (beginning ~2000): passive nanostructures, illustrated by nanostructured coatings, nanoparticles, dispersion of nanoparticles, nanocomposites, and bulk nanostructured materials — nanostructures made of metals, polymers, ceramics; bio-building blocks.

²³ M.C. Roco, “Nanoscale science and engineering: Unifying and transforming tools,” *AIChE Journal*, Vol. 50, No. 5, May 2004, 890-897.

- **Second Generation** (beginning ~2005): active nanostructures, illustrated by transistors, amplifiers, targeted drugs and chemicals, biological and non-biological sensors, actuators, and adaptive structures.
- **Third Generation** (beginning ~2010): three-dimensional nanosystems and systems of nanosystems using various synthesis and assembly techniques such as bio-assembly, networking at the nanoscale, and multiscale architectures.
- **Fourth Generation** (beginning ~2015): materials by design and heterogeneous molecular nanosystems, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices, and from their engineered structures and architectures will emerge fundamentally new functions. Since the path from fundamental discovery to nanotechnology applications takes about 10–12 years in recent nanotechnology developments, now is the time to begin exploratory research in 3D integrated, heterogeneous devices, structures, and systems that involve materials by design and molecular nanosystems.

The emphasis is on broadly applicable processes applied primarily to three-dimensional structures. There are technical barriers to high-volume and predictable nanomanufacturing for each of these four generations of product types. While some manufacturing knowledge may be drawn from existing manufacturing enterprises, much of the future manufacturing paradigms will require new science and engineering knowledge, particularly with respect to the third and fourth generation of product types.

Figure 3-1 depicts the envisioned development phases for nanomanufacturing technology. While the figure indicates definite time scales for each of these phases, timing may change as development evolves, and these various generations of development will continue to be worked beyond the time horizons indicated in the figure as manufacturing processes and systems continue to be optimized.

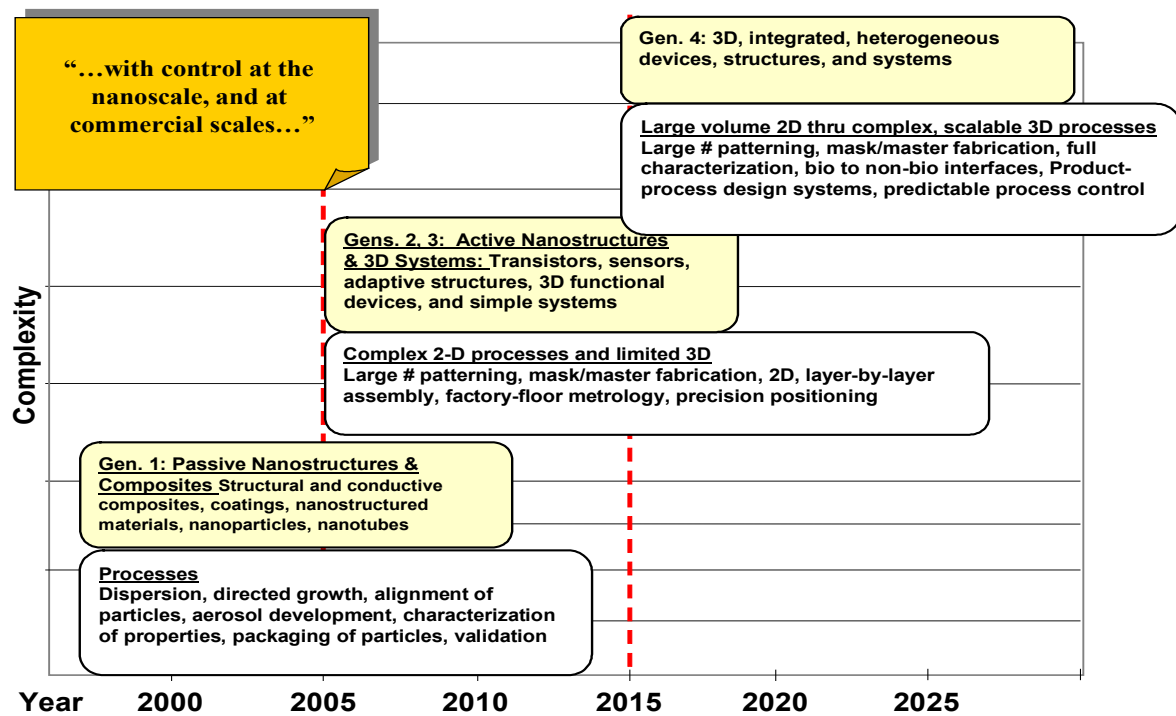


Figure 3-1: Phases of nanomanufacturing development.

Technical Areas for R&D Focus

Technical areas for R&D focus include novel nanomanufacturing methods that are "top down" and those that are "bottom up." The former involve further scaling down, or miniaturization through modification of existing methods. The decreasing size (and increasing density) of transistors manufactured by the semiconductor industry is an example. Nanomanufacturing R&D also includes technologies and processes where complex structures are built with atom-by-atom control. In such mechanically based nanosystems, nanoscale cogs, gears, and bearings are integrated to make nanoscale robot factories, probes, and vehicles that mimic the sophisticated nanoscale machines typical in cell biology.

This approach includes molecular motors perhaps analogous to those that make up our muscles and which can convert chemical energy to mechanical energy with similarly high efficiencies.

A number of NNI workshops have been held to identify the critical needs of nanomanufacturing. Table 3-2 summarizes three broad areas of need and some of the R&D challenges that align with various agency missions and national and industrial needs.

Table 3-2: Nanomanufacturing Focus Areas and R&D Challenges

Focus Areas	Nanomanufacturing R&D Challenges
Infrastructure Development and Partnerships	<ul style="list-style-type: none"> • Providing access to and transfer of results from shared resources and facilities • Instrumentation and metrology • Development of standard data, methods, and practices
Integrated Product and Process Design Tools and Systems	<ul style="list-style-type: none"> • Development of product and process models • Innovative scale-up and modular building blocks • Integrating top-down and bottom-up processes • Combining multiple processes • Design automation tools and software for support of applications of nanosystems • Beyond-optical-resolution probing, production metrology • Use of living systems as nanomanufacturing factories
Workforce Needs, Societal Impact, Environmental Impact, and Human Health and Safety	<ul style="list-style-type: none"> • Providing an educated, globally competitive workforce to support nanomanufacturing industries • Designing in and assuring the environmental health and safety of nanoscale products and processes (entire life-cycle)

Key R&D challenges for the first two of these focus areas are discussed below. The last category shown in Table 3-2 transcends all three IWG priority topics and is discussed in Chapter 5 of this report. The IWG considers that addressing these social issues responsibly and proactively will be vital to the long-term success of any R&D endeavor related to nanomanufacturing.

Infrastructure Development and Partnerships

A strong physical and cyber infrastructure for R&D is a major requirement for innovation. Tools and facilities such as state-of-the-art instruments, multidisciplinary laboratories, standardized methods, reference data, and calibrated standards stimulate and enable new discoveries and transition of discoveries to products for the marketplace. The use of such assets will enable the development of the tools of tomorrow, which will in turn facilitate manufacturers' ability to transition ongoing technological discoveries and innovations into commercial production. This is a critical component of cost-effective scale-up of production volumes — going from prototype fabrication to market-appropriate lot sizes in a commercially viable manner. The innovation process from research lab to marketplace involves government, academia, and industry.

The Government has a role in developing tools that are broadly used by all of the stakeholders in the innovation process. Development of standardized methods, reference data, and calibrated standards typically is not pursued in basic research carried out at universities. Because their value tends to be non-appropriable and generic such that entities usually cannot retain, or appropriate, their value and it diffuses broadly, these tools are not profitable for individual companies to develop.

Federal agencies typically have multidisciplinary R&D centers, traditions of access to unique facilities, and missions to provide infrastructural support and identify research targets in the areas of infrastructure and partnerships. As such, they are strategi-

cally positioned to assist in initiating and maintaining critical infrastructure for this emerging R&D area. As describe earlier, the NNI has established a broad network of user facilities and research centers to provide such support.

Important infrastructure that should be sustained or expanded include

- Geographically distributed nanomanufacturing research and nanofabrication user facilities
- Wide access to facilities through development of capabilities for remote manufacturing with telefabrication and telecharacterization, and incentives to promote sharing of facilities, staff time, and other resources
- Standard nomenclature; reference materials; procedures for synthesis and evaluation of materials; standard libraries of components, processes, and models; and standard practices for modeling, simulation, and information processing
- Strategies for promoting technology transfer and commercialization activities, including nanomanufacturing roadmaps, identifying opportunities for small business incubation and growth, and handling of intellectual property to accelerate manufacturing technology transfer to the marketplace

- Engagement of scientists and engineers in fields of health, environment, social and economic sciences to develop important sources of knowledge and expertise
- Bringing underrepresented groups into this exciting new field, and addressing the challenging issues of foreign visiting scholars for promotion of international precompetitive research and education collaborations

Access to shared infrastructure. A key aspect of infrastructure is the development of, verification of, and provision of access to advanced analytical tools. The technical scope and capital requirements for developing the tools necessary for R&D on the nanoscale is such that it will require cooperation among industrial, academic, and government laboratories. In addition to needing advanced analytical and measurement tools, researchers will need accessible libraries of molecules for controlling complex nanomanufacturing assemblies, for example, RNA libraries that can effectively turn off specific elements of cellular machinery.

Improved information exchange and development of uniform usage policies will be key to improving collaboration between government and industry. Intellectual property issues that exist regarding the use of national user facilities must be resolved. Successful analytical tools developed in broad-based user facilities must be transferred to instrument manufacturers for refinement and eventual production and

commercial distribution. Instrument manufacturers must participate in the development of new measurement technologies and cost-effective means for controlling the environmental interferences, such as vibrations or airborne contaminants, which can undermine measurement accuracy and quality control.

Instrumentation and metrology.

Instrumentation and metrology are essential elements of any manufacturing process, and nanotechnology processes will be no exception. Industry will need new metrology tools to meet the unique challenges of a nanoscale production environment and to ensure that manufacturers can make the measurements critical for product and process conformance. Metrology will need to be brought onto the production floor, where issues such as product throughput, process control, and safety are critical. The potentially large variety of nanomanufacturing applications will require a diverse set of metrology tools and infrastructure suitable for both low- and high-volume markets.

An effective vision for nanomanufacturing metrology and instrumentation is a tiered infrastructure similar to the metrology infrastructure that exists for conventional scales of manufacturing. Such an infrastructure incorporates specialized in-line metrology tools for rapid and precise measurements for process control during manufacturing; these are backed up by slower yet more accurate and general tools off the manufacturing floor or in national laboratories.

Standards development. Another key aspect of infrastructure is the development of supporting standards. Reference standards, standardized methods for synthesis and analysis, and standards for effective information management and communication are vital. Researchers, manufacturers, and end users must be able to reliably and confidently compare chemical, physical, and biological properties of materials. Design engineers need material specifications that are truly representative of the materials to be used and the applications. Consumers must be able to compare product attributes.

These requirements present a range of challenges. The form of current calibration standards often is not compatible with new analytical tools at the nanoscale. A lack of common protocols for characterizing processes and equipment hinders collaboration and understanding. No well-defined standard protocols and formats exist that facilitate access to models that are developed for nanotechnology processes. Absence of a standard nomenclature that spans disciplines impedes what could be valuable communication across disciplines. Development of accurate nanoscale or smaller length standards requires advances in several areas of science and technology, whereby multiple techniques for measurement of physical, chemical, and biological properties need to be cross-validated.

It is also important that efforts to address standards development be coordinated with those activities that already exist within the scientific and manufacturing standards community through standards developing organizations such as the International Organization for Standardization (ISO), the American National Standards Institute (ANSI), the American Society of Manufacturing Engineers (ASME), the Institute of Electrical and Electronics Engineers (IEEE), and the American Society for Testing and Materials (ASTM) International, among others.

In addition, the control, data acquisition, and data analysis characteristics of analytical tools for standardized nanomanufacturing present cyber infrastructure standardization challenges. Large data sets will have to be processed, stored, managed, interpreted, and disseminated. Identifying statistically significant trends will be difficult. Managing access to data will also be a challenge. The sheer volume of data and its effective application will require extraordinary computational and management capabilities, as well as the development of organization systems and structures that foster communication and assist in the application of new technologies.

Integrated Product and Process Design Tools and Systems

Integrated Product and Process Design is of proven value to manufacturers. It is expected to be of even greater value to tomorrow's manufacturers of nanoscale products, resulting in an increasing value of research in this area.

Additionally, the development of and access to these systems are closely related to the IWG priority in Intelligent and Integrated Manufacturing (Chapter 4). One of the principal need areas identified by the IWG relating to IIM is Predictive Tools for Integrated Product and Process Design and Optimization. The IWG's coordination of focus across its technical priority areas will allow needs to be addressed in a timely and efficient manner. The IWG has identified two major R&D challenge areas related to product and process modeling for nanomanufacturing, as outlined below.

Design, modeling, and simulation.

To control the assembly and incorporation of nanoscale elements into micro- and macroscale products, an understanding is required of many different physical, chemical, and material phenomena, such as surface chemistry, electrostatics, fluid flow, and adhesion. And because nanoscale devices will be capable of functionality that is dependent upon unique characteristics and interactions of matter at the nanoscale, there is a strong interdependence between product design and manufac-

turing processes. Thus, nanomanufacturing requires a new holistic approach, beyond what is taken today on larger fabrication scales, with various branches of science and engineering coming together to deal with the complexity of the interacting phenomena.

To produce complex, highly functional microscale products, leading-edge manufacturers today use a Design-for-Manufacture approach that integrates the product design process with the manufacturing process design. But this approach poses many new challenges at the nanoscale, not the least of which is process variability, which can dominate manufacture at the nanoscale. Accordingly, nanoscale manufacturing equipment manufacturers must demonstrate to their customers that their equipment can adequately control process variability. Statistical models of yield, performance, and failure will need to be developed to support design and manufacture process decision making. Again, this issue is highly relevant to the IIM priority area (Chapter 4), and the IWG will work to ensure that nanomanufacturing applications are included among the focus areas of IIM.

Modeling processes across many orders of magnitude in length and time scales.

Process and performance models are a key element of design and manufacturing modeling and simulation. Accurate predictive models and simulations are needed that can link nanoscale properties across time and length scales to specific macroscopic properties. This is a significant challenge, as scales need to be bridged across as many as nine orders of magnitude in length from the subnanometer to meter, and across as many as seventeen orders of magnitude in time from femtoseconds to hours.

Current models and simulations predict atomistic behavior from quantum calculations as well as predict macroscopic continuum behavior of particles and structures. But the current models and simulations are stretched beyond the limits of validity when applied across the scales of nanotechnology. Expertise needed to significantly improve modeling capabilities is currently dispersed across research centers, while the computing requirements for current simulation methods are very large and expanding. Research is needed to improve computational capabilities through shared and innovative architectures. Emerging models will need to be validated by experimental data covering the full range of proposed applications.

Material and Manufacturing Processes

Delivering the many anticipated nanotechnology products of the future will require entirely new manufacturing processes. These include cost-effective methods for synthesizing and processing nanotubes, particles, fibers, and quantum dots; nanotube dispersion in nanocomposites; atomic-layer deposition for nanoelectronics; positioning, imaging, and measurement at nanoscale resolution; and modeling of material-energy interactions and manufacturing processes from nanoscale to macroscale. Several of these manufacturing processes are currently being realized, and they will need to be refined continuously to fully realize the promise of future nanotechnology products. Four key challenges in material and manufacturing processes are summarized below.

Scale-up and modular nanomaterial building blocks. Scale-up of manufacturing processes from small lot sizes to mass production and modular building blocks pose the first of four key challenges in the material and manufacturing processes. Process engineers need approaches that use mass production techniques, modular assembly with building blocks, and integrated assembly to reduce costs and accelerate the entry of nanomaterials into commercial applications.

Unit operations that comprise these production methods must be scaled successfully and reproducibly from laboratory processes into production rates, while preserving the inherent nanoscale properties in the finished materials. Such scaling will rely on basic physical and thermodynamic data that do not currently

exist. While chemical processes typically deal with a huge number of structures with relatively simple assembly processes, and electronic processes typically deal with a much smaller number of structures but highly complex assembly processes, nanomanufacturing will be called upon to deal with both a huge number of structures and a highly complex hierarchical assembly, and it requires major innovations in such areas as patterning, templating, and surface functionalization.

Integrating bottom-up and top-down nanoscale assembly processes. Integration of bottom-up and top-down nanoscale assembly processes poses the second of four key challenges. Today's first-generation nanoproducts are frequently manufactured with traditional manufacturing techniques and unit operations, and they can be prohibitively expensive for many applications. Adaptation to nanomanufacturing processes is problematic.

As electronics device elements and features attain nanoscale dimensions, patterning and processing become ever more expensive and difficult to extend into three dimensions. Macroscopic assembly processes such as crystallization and mixing do not readily lend themselves to the fabrication of hierarchical systems of nanostructures. Partial resolution of this dilemma must come from far more sophisticated preparation of the nanostructure building blocks, where nanostructures on specially prepared surface features lead to the assembly of hierarchical systems. Research is being conducted on aspects of this approach.

Ultimately, this research must also bear in mind the requirements posed by scalable, cost-effective manufacturing, by robust and reliable production methods consistently and correctly controlled at the atomic scale, or by production that must be safe and environmentally friendly.

Combining multiple assembly processes. Combining multiple assembly processes poses the third challenge to manufacturing processes. An example is biomimetic self-assembly, where preexisting parts or disordered components of a preexisting system form structures of patterns in a way that mimics the methods and systems found in nature. The science of crossing material size-scale boundaries and integrating nanomaterials into the macroscale world is still in its infancy.

Moving beyond optical-resolution probing and metrology. Advanced analytical tools for probing and metrology that extend beyond optical resolution pose the fourth challenge to manufacturing processes. Advancements in high-volume, cost-effective production depend on development of next-generation instrumentation for accurate and rapid characterization of nanosized elements. Optical methods, which can be accurate, fast, and integrated in-line for process control, are reaching their detection and resolution limits for probing nanoscale structures.

Other methods that do not share optical limitations have their own limitations that need to be overcome. Many high-resolution imaging and microscopy methods are limited to surface examination, making 3D imaging methods such as optical coherence tomography and near-field scanning optical microscopy important. Current spectroscopy and scattering methods using X-rays or neutrons provide structural information at the nanoscale averaged over a large volume, not at the desired one nanometer or less. The atomic force microscope (AFM) and scanning tunneling microscope (STM) are capable of measuring chemical, physical, electrical, magnetic, and dimensional properties with one-nanometer resolution but are limited in raster speeds. X-ray, neutron, and electron spectromicroscopy systems need to be further developed to yield accurate three-dimensional imaging and measurement capabilities.

Use of Living Systems as Nanomanufacturing Factories

Cells are remarkably complex systems that include “nanomachinery” capable of manufacturing a variety of nanomaterials (especially proteins and protein complexes) and other smaller molecules. These nanomanufacturing “factories” have been used with some success for health applications such as the production of human insulin and human growth hormone, and they demonstrate promise for potential use in the manufacture of non-health-related nanoassemblies such as photovoltaic or food production devices.

Key challenges in this area include the need for additional basic research on the structure and function of potential nanomaterials and nanoassembly systems, as well as research on the integration of these complexes with nonliving systems. There exists a need for basic research and engineering of cellular metabolics for enhanced productivity, improved scale-up models, high-throughput biological separation technologies, and protein-specific online process sensing and control technologies. Other cell-based nanomanufacturing for healthcare involves the delivery of cells directly to the site of disease. An example is the attempt to implant cells into the brain where they might manufacture dopamine for the treatment of Parkinson’s disease. A key challenge for this application of nanomanufacturing is control of the manufacturing plant. Production must be matched to need, and this requires feedback control of production based on need. Also, other machinery within the cell needs to stay turned off. Additional fundamental understanding of the control of cell processes will be a key challenge in advancing such manufacturing techniques.

R&D Opportunity Areas

Despite the groundbreaking efforts noted above in establishing infrastructure and promoting promising nanomanufacturing-related research, there still remain significant areas of manufacturing R&D that need to be addressed in order to realize the benefits of nanotechnology. Several opportunity areas are noted below.

Metrology and Standards

The nanomanufacturing community feels some urgency to make progress in this area. European and Asian competitors are skilled, and their investment in nanotechnologies has been strong. Experts expect that within the next ten years, many of the newly designed advanced materials and manufacturing processes will be built at the nanoscale and require nanoscale measurement methodology and standards to successfully manufacture products.

As manufacturing processes and products become ever more sophisticated, the key battlefields of 21st century manufacturing will depend to a greater extent on excellence in measurement technology: If it cannot be measured, it cannot be manufactured reliably. Standards are key infrastructural tools. This is true across the board in manufacturing. However, it is especially true in the rapidly developing field of nanomanufacturing, where it can be necessary to locate, track, and manipulate individual molecules and atoms. Global standards are enablers for industry and society to have confidence in the quality and safety of manufactured nanomaterials and emerging nanoscale devices and systems.

The novel properties of nanoscale structures make their production and characterization subject to unique challenges; conventional processing approaches are not generally applicable, and trusted measurement approaches cannot yet be relied on for characterization. Without broadly accessible standards for nanotechnologies that are based on sound science, market access will be limited by lack of common technical specifications and by public safety concerns. In addition, without broadly accessible measurement techniques that address materials and process selection and component design and reliability, innovation of products based on nanoscale structures will be impeded.

Also, there is a critical need to coordinate developing standards with the activities already underway within national and international standards-developing organizations such as those identified earlier in this chapter.

Control at the Nanoscale

Nanomanufacturing processes must have effective control systems with accurate, timely measurements and rapid data assessment and response parameters. Integrating the process control components at the nanoscale will require a long-term commitment to R&D in diverse science and technology fields.

Collaborative Tools

Collaboration is not as extensive today as it could be to leverage assets and knowledge and move nanomanufacturing forward. There is a need for a public portal to disseminate information and to facilitate collaboration and partnering. Collaborative tools would facilitate

coordination and exchange of key information and knowledge that would benefit the entire nanomanufacturing community as well as the wider manufacturing community. They would also help education environments to facilitate and support learning within and across institutional boundaries.

Nanoelectronics

There are abundant research opportunities that focus on the challenges that hinder widespread commercial use of nanotechnologies for electronics. To address the performance requirements in nanoelectronics requires collective research efforts on materials, structures, devices, circuits, systems, and architectures. As an extension of the microelectronics industry, this area requires joint work with industrial partners who will support proof-of-concept research efforts that can be developed quickly into manufacturing-scale systems.

Nanobiotechnology and Bio-Nanomanufacturing

Nanobiotechnology is a field that applies nanoscale principles and techniques to the understanding and transformation of biosystems (living or nonliving) and that uses biological principles and materials to create new devices and systems integrated from the nanoscale. The integration of nanotechnology with biotechnology, as well as with information technology and cognitive science, is expected to accelerate in the next decade. The convergence of nanoscale science with modern biology and medicine is a trend that will depend upon focusing nanomanufacturing R&D on useful applications such as production of monoclonal antibodies, agents for gene and drug delivery, and targeted theranostics.

Biomimesis and Self-Assembly

Self-assembly and biomimetic techniques have mainly occurred, heretofore, as demonstrations that are largely limited to the laboratory scale; they have not been used effectively at the commercial level. The feasibility of using biological systems to generate nanomaterials on a full manufacturing scale needs to be explored alongside other novel techniques for modular, hierarchical, self-assembly. Biological systems have evolved sophisticated manufacturing subsystems such as an ability to automatically recover from process upsets, self-assembly, and recycle wastes. Cells can also efficiently transform matter into energy at ambient temperatures and pressures. These techniques could eliminate by-products and waste typical of conventional manufacturing, reduce raw material and energy needs, and minimize labor costs.

Needs Beyond R&D

There remain nontrivial needs related to workforce training and education for nanomanufacturing applications, especially at the technician and engineer levels. Also, the appropriate handling of intellectual property issues associated with shared access to nanomanufacturing infrastructure assets is a non-research area that could impede technical progress.

Recommendations and Next Steps For the IWG

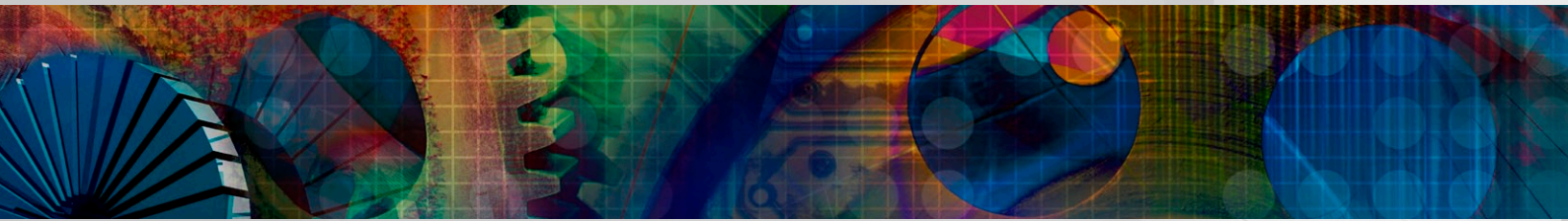
The IWG's work on nanomanufacturing must be closely coordinated with the aims of the NNI. In this regard, several connections have already been made at the individual agency level as well as between the IWG and the Nano-scale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC, which serves as the point of contact on Federal NNI activities, conducts public outreach, and promotes the transfer of the results of Federal nanotechnology R&D to commercial use and public benefit. This connection will be strengthened through cross-planning and cooperation in joint activities. The IWG will use its manufacturing R&D perspective, expertise, and agency resources to complement the efforts of the NSET Subcommittee and will continue to work together with NNI agencies and offices to sharpen their focus on the manufacturing component of nanotechnology.

Related to this, a number of specific activities recommended below will ensure that IWG nanomanufacturing activities complement and augment nanomanufacturing activities of the NNI. This will in turn ensure that the critical area of nanomanufacturing is addressed broadly and deeply across the Federal R&D enterprise in a manner that is appropriate and commensurate with the Nation's needs in this area.

- The IWG should coordinate with the aims, activities, and agents of the NNI. This objective can be achieved at least in part through maintaining a strong liaison relationship with the NSET Subcommittee of the NSTC.
- The IWG should plan, as needed, nanomanufacturing workshops that continue to define nanomanufacturing technology-specific needs and issues and that lay out strategies for coordinating the Federal effort to address them. These workshops should be jointly planned and conducted with the NSET Subcommittee, as appropriate.
- The IWG will assist in disseminating the findings of a workshop on Instrumentation, Metrology, and Standards for Nanomanufacturing that was planned with NSET and conducted in 2006, that built upon the similar NNI workshop held in 2004 specifically focusing on metrology and instrumentation as it applies to nanomanufacturing.
- The IWG should work with the NNCO, which provides staff support to the NSET Subcommittee on NNI activities, to conduct a rigorous analysis of the many recent NNI reports as one basis for a comprehensive working plan to address nanomanufacturing, and also to address critical gaps identified in NNI workshops.
- The IWG should promote better engagement between the Federal Government and industrial sectors — especially the manufacturing interests from those sectors — to seek their insights into Federal roles and investments that would be helpful to them.
- The IWG should continue to promote communication and coordination between its Nanomanufacturing focus and its other two technical priority areas of Manufacturing R&D for Hydrogen Technologies and Intelligent and Integrated Manufacturing.

Chapter 4

Intelligent and Integrated Manufacturing



Definition and Scope

The IWG defines intelligent and integrated manufacturing as the application of advances in software, controls, sensors, networks, and other information technology to achieve

- Rapid, cost-predictive development of innovative products and processes
- Highly productive, safe, and secure production machines and systems that are easily adapted and reconfigured in response to changing conditions and new opportunities
- Optimized, agile, and resilient enterprises and supply chains

The IWG's Intelligent and Integrated Manufacturing priority area is broad in scope; it encompasses mid- to long-term R&D in support of essentially all manufacturing-specific applications of computers and software. The overall objective is to enable and encourage applications that can significantly improve the production, interorganizational, and business capabilities of U.S. manufacturers, regardless of the size of their firms or where they reside in the supply chains and collaborative, networked enterprises of the future. Advances in integrated and intelligent manufacturing capabilities will enable companies to optimize knowledge, technology, and talent to achieve sustainable competitive advantages.

Intelligent and integrated manufacturing R&D builds upon the foundational information technology research performed under the Federal Networking and Information Technology Research and Development (NITRD) Program, an interagency effort organized under the National Science and Technology Council.²⁴ One of the NITRD program's top three goals is to "advance U.S. productivity and competitiveness through long-term scientific and engineering research in information technology."

²⁴ More information on the NITRD Program is available at <http://www.nitrd.gov/>.

Manufacturing represents a key area of opportunity for translating NITRD-enabled technologies and capabilities into tangible benefits for U.S. industry and the national economy. In fact, the Nation's manufacturing sector "has led the way in terms of IT investment, transformation, and productivity growth."²⁵ At the same time, improvements in manufacturing capabilities have paved the way for a succeeding series of "next-generation" information technologies. For example, advances in intelligent and integrated manufacturing have been essential to the long-sustained record of progress in the miniaturization and high-volume production of integrated circuits and data storage devices. Such "next wave" products then become the platform for further advances in communication, networking, and software applications. The resulting capabilities are leveraged in scientific instruments and services that facilitate research progress, which ultimately may lead to far more advanced and more capable intelligent and integrated manufacturing tools. This priority area for manufacturing R&D, therefore, plays a critical supporting role in the continuing enhancement of the Nation's IT infrastructure, which underpins the performance of businesses, industries, and the entire U.S. economy.

Federal R&D and Coordination Efforts

A major focus of Federal R&D in intelligent and integrated manufacturing is fostering the underlying technical infrastructure:

- Process models and simulation
- Scientific and engineering databases
- Test and measurement methods
- Technical bases for both physical and functional interfaces between the components of systems technologies

These kinds of generic technical tools can significantly enhance the efficiency of R&D, design, production, and marketing, as well as increase returns realized on organizational investments in IT across all supply chain levels.²⁶ However, development of these infrastructural technologies often does not bring returns that are easily appropriated by individual private sector organizations that might devote resources to these R&D efforts. The Federal government can play a critical role assisting in the development of these widely useful capabilities.

Advancing the infrastructure for intelligent and integrated manufacturing also will contribute directly to complementary robotic and intelligent systems research activities that Federal agencies fund and conduct in support of their missions, including national defense, space exploration, and processing and storage of nuclear materials. For example, it would

²⁵ Catherine Mann, *Globalization of IT Services and White Collar Jobs: The Next Wave of Productivity Growth*, Institute for International Economics, Policy Brief No. PB03-11, Washington, DC: IIE, December 2003.

²⁶ Gregory Tasse, *R&D and Long-Term Competitiveness: Manufacturing's Central Role in a Knowledge-Based Economy*, NIST Planning Report 02-2, February 2002, available at <http://www.nist.gov/director/prog-ofc/report02-2.pdf>.

accelerate progress toward DOD goals to implement “net-centric” communication, which would improve the readiness and cost-effectiveness of military systems. The anticipated capabilities of network-centric supply chains would help ensure domestic production — and assured availability — of sophisticated weapons systems and components. Similarly, agency-supported work on distributed computing, modeling of complex systems, knowledge management, systems compatibility, and other areas applicable to next-generation manufacturing should be leveraged in Federal R&D focused on intelligent and integrated manufacturing.

Increased Federal agency coordination and focus in this important technology area will strengthen the Nation’s technical infrastructure, creating an environment that fosters innovation, economic efficiencies, and private sector investments. All are necessary to ensure future productivity increases and to enhance the competitive performance of U.S. manufacturers.

Current Federal R&D Efforts

A number of R&D activities in intelligent and integrated manufacturing currently are carried out by NSF, DOC/NIST, DOD, DOE, NASA, and USDA. Examples of these efforts were gathered during an Interagency Program Review²⁷ conducted in 2003 by the Government Agencies Technology Exchange in Manufacturing (GATE-M) effort, the predecessor of the IWG on Manufacturing R&D.

NSF funds a significant amount of basic R&D related to intelligent and integrated

manufacturing, most of it performed at academic institutions. This R&D work is distributed among four NSF program areas: Manufacturing Machines and Equipment, Manufacturing Enterprise Systems, Engineering Design, and Materials Processing and Manufacturing. Moreover, NSF supports several university-based Engineering Research Centers whose work bears on intelligent and integrated manufacturing problems.

Efforts at NIST tackle measurement science and standards challenges and provide supporting test methods, tools, and testbed environments and facilities. Several NIST programs and projects are focused specifically on intelligent and integrated manufacturing. These include Smart Machining Systems, Manufacturing Interoperability, Industrial Control System Security, Infrastructure for Integrated Electronic Design and Manufacturing, and Advanced Manufacturing Processes.

As would be expected, work at DOD, DOE, NASA, and USDA is focused on developing tools and technologies enabling the advanced manufacturing capabilities needed to accomplish agency missions. For example, DOD is working to develop requirements-based cost models. Such models would enable value-based optimization in the requirements-definition phase — well before product designs are finalized and costs are locked in. DOE carries out projects to develop intelligent manufacturing operations to produce high-quality components for the Nation’s nuclear weapons stockpile. NASA is developing sophisticated manufacturing simulation capabilities, integrated design and analysis tools, and solid freeform fabrication to support space vehicle manufacturing opera-

²⁷ David C. Stieren, *The 2003 Interagency Program Review of the Government Agencies Technology Exchange in Manufacturing (GATE-M)*, NISTIR 7076, Gaithersburg, MD: National Institute of Standards and Technology, December 2003.

tions. Current activities supported by USDA mainly focus on developing advanced computer-aided design and manufacturing technologies for food products, processes, and equipment to enhance food safety, quality, and value.

This brief review of Federal R&D efforts relevant to the IWG's Intelligent and Integrated Manufacturing focus area reveals significant commonalities among agency interests and activities. However, because these programs have been planned and executed independently by the agencies involved, there can be missed opportunities to benefit from each others' efforts. Through recent and planned activities, the IWG is working to strengthen interagency collaborations and maximize the benefits of Federal investments in intelligent and integrated manufacturing R&D. This includes working with the NITRD Program to coordinate manufacturing efforts to help advance U.S. productivity and competitiveness.

Relationship Between Intelligent and Integrated Manufacturing R&D and NITRD

In addition to Federal R&D activities directly focused on aspects of intelligent and integrated manufacturing, many complementary efforts are being carried out under the multiagency NITRD Program, which had a budget of nearly \$3 billion in fiscal year 2006.²⁸ As with the NNI, NITRD has identified priority Program Component Areas (PCAs) for Federal work in Networking and Information Technology research and development. Several of the NITRD PCAs support work that can lead to advanced networking applications in manufacturing processes and organizations. At the same

time, the IWG's focus on Intelligent and Integrated Manufacturing represents a key opportunity area for transferring and converting NITRD results into economically significant impacts. Specific points of leverage between NITRD PCAs and manufacturing R&D are summarized below.²⁹

NITRD PCA: Software Design and Productivity (SDP). R&D efforts in the Software Design and Productivity PCA will lead to fundamental advances in concepts, methods, techniques, and tools for software design, development, and maintenance. These can narrow the widening gap between the need for usable and dependable software-based systems and the ability to produce them in a timely, predictable, and cost-effective manner. This topic area is of great relevance to the IWG's Intelligent and Integrated Manufacturing topic, given that six out of thirty-one projects identified in a 2005 IEEE Spectrum magazine article, "Software Hall of Shame," involved enterprise resource planning and other large software systems for manufacturers.³⁰ SDP is the PCA most synergistic with Intelligent and Integrated Manufacturing. Closely corresponding needs and issues are being addressed in projects in the following topic areas:

²⁸ See <http://www.nitrd.gov>.

²⁹ NITRD PCA descriptions are from NITRD, *Supplement to the President's Budget for FY 2007*, February 2006, available at <http://www.nitrd.gov/pubs/2007supplement/>.

³⁰ Robert N. Charette, *Why Software Fails*, *IEEE Spectrum*, September 2005.

- Software design methodologies
- Tools for software testing, analysis, and verification
- Semantics, design, and implementation of programming languages
- Scalable software architectures
- Techniques for handling complex combinations of requirements, such as meeting real-time constraints and coordinating control in an embedded failure-prone environment
- Automated generation of test suites for software integration
- Supply chain software interoperability
- Interface standards for manufacturing control systems
- Product representation schemes for interoperability among computer-aided engineering systems
- Model-based software engineering for real-time systems
- Methods to demonstrate that evidence gathered during system design and testing supports dependability and real-time performance claims for specific systems

Indeed, many current agency intelligent and integrated manufacturing R&D activities are reported in the NITRD Program's Annual Supplement to the President's budget under the Software Design and Productivity PCA.

NITRD PCA: High Confidence Software and Systems (HCSS).

R&D activities in the High Confidence Software and Systems PCA aim to fundamentally advance the theoretical foundations and the technologies necessary to achieve, affordably and predictably, high levels of safety, security, reliability, and survivability in critical systems. HCSS activities related to intelligent and integrated manufacturing include multiagency research on

- Assured, composable, secure, real-time operating systems and middleware
- Basic research and technology development for high-confidence embedded systems, hybrid control, and distributed systems
- Methods for demonstrating that large software systems are free from flaws

If the manufacturing community and the IWG provide input and contribute to these efforts in particular, the results can be directly applicable and beneficial to manufacturing.

NITRD PCA: Human-Computer Interaction & Information Management (HCI&IM).

R&D in the NITRD HCI&IM PCA focuses on developing technologies that enable computing, information, and communications systems to understand, adapt to, and serve the many needs of diverse users, including interactive capabilities for manipulation, analysis, and control. Research related to intelligent and integrated manufacturing includes

- Advanced decision support technologies
- Intelligent robots and machine vision
- Interactive systems technologies, including user interfaces and human-robot interactions

However, few of these projects focus on manufacturing as an application domain. For example, most of the robotics work addresses mobile robots in non-manufacturing arenas such as space, defense, surveillance, and search and rescue. The knowledge and technologies spawned by these projects have the potential to serve as springboards for innovative IT applications in manufacturing.

NITRD PCA: Cyber Security and Information Assurance (CSIA).

The NITRD CSIA PCA focuses on R&D to prevent, resist, detect, respond to, and/or recover from actions that compromise or threaten to compromise the availability, integrity, or confidentiality of computer-based systems. Topics of particular relevance to intelligent and integrated manufacturing include

- Secure process control systems
- Wireless security
- Secure RFID Applications

The evolution toward intelligent and integrated manufacturing will elevate the importance of maintaining a secure and reliable communications environment.

NITRD PCAs: High-End Computing (HEC) Infrastructure and Applications; HEC Research and Development.

Activities of these two NITRD PCAs focused on high-end computing target advanced computing systems, applications software, data management, and the underpinning infrastructure necessary to support research to keep the United States at forefront of 21st century science, engineering, and technology and, at the same time, further the missions of Federal agencies. Although HEC capabilities tend to be most immediately applicable to computer-intensive scientific applications, there are efforts, such as immersive visualization and architectures for cognitive information processing, that will ultimately provide important capabilities for intelligent and integrated manufacturing.

NITRD PCA: Large-Scale Networking (LSN).

Agencies participating in research related to the NITRD LSN PCA aim to pave the way for leading-edge networking technologies, services, and techniques to enhance performance, security, and scalability. R&D topics related to intelligent and integrated manufacturing include

- Wireless and sensor networking
- End-to-end network performance measurement
- Networking security

Research Challenges and Opportunities

On the basis of a survey of manufacturing industry roadmaps as well as interactions with industry representatives at the IWG public forums and other related workshops, the IWG has identified four technical areas for R&D that pose significant challenges:

1. Predictive tools for integrated product and process design and optimization
2. Intelligent systems for manufacturing processes and equipment
3. Automated integration of manufacturing software
4. Secure manufacturing systems integration

Predictive Tools for Integrated Product and Process Design and Optimization

Success in manufacturing depends increasingly on the ability to rapidly translate new technologies into market-ready products tailored to customer requirements. Modeling and simulation tools are key enablers for accelerated product development and efficient insertion of new technologies. A substantial amount of product development and testing can now be done in a virtual environment. However, manufacturers cannot yet simulate the behavior of many materials and manufacturing operations (including assembly) at a very high level of fidelity.

Development of metal-cutting process plans from design data, for example, is still an ad hoc, empirical process that results in suboptimal machine and tool utilization. Key process-engineering decisions, such as the selection of appropriate cutting tools, machining speeds, and feed rates, typically are based on costly, trial-and-error prototyping or on recommendations from outdated handbooks. Not surprisingly, the resulting “solutions” are far from optimal.

The quality and accuracy of process-related decisions could be improved dramatically by using physics-based models that reliably predict the behavior of manufacturing processes. The state of the art in predictive modeling of machining operations is severely limited because measurement and materials characterization capabilities lag model development. In other words, current models give impressive qualitative results, but there are virtually no substantiating data to provide confidence that the results they generate are correct. The challenges of generating these data include the wide range of materials and properties for which reliable measurements are lacking. Making accurate measurements under conditions that mimic the extreme temperatures and material deformation rates encountered in machining poses another set of challenges.

New, standard, interoperable design and manufacturing tools must be developed to reduce the development cycle time, cost, and extensive software integration associated with product applications in key defense, space, and homeland security sectors. Examples include unmanned air vehicles; sensitive, reliable sensor networks for detection of chemical, biological, and other threats; and personal protective equipment.

From the perspectives of DOD and DOE's National Nuclear Security Administration, weapon system development lead times have grown to the point where U.S. forces may be deprived of capabilities that the latest technology offers. For example, the avionics suite for a typical new aircraft is two generations behind the current electronics state-of-the-art by the time the system is first deployed. Not only do these long lead times penalize our military capability, but they also drive cost increases in weapon system development, production, and sustainment. A major contributor to these long lead times and cost increases is the vast number of design changes that are necessary to achieve a manufacturable system. Repeated rounds of testing, evaluating, modifying, and retesting consume a highly disproportionate share of the time and money required to move a product from concept to delivery.

Similarly, NASA has seen lead times associated with aerospace hardware development slow to the point that the most efficient, cost-effective methods are not being used in satisfying fundamental mission objectives. Studies indicate that design and analysis tools continue to mature quickly, far outpacing progress in manufacturing and process tools. Manufacturing capability is not adequate to support advances from software tools within other disciplines. NASA and the aerospace community are interested in advancing capabilities for comprehensive life-cycle manufacturing techniques that exploit modeling and simulation tools and virtual environments in order to accelerate manufacturing process development.

Intelligent tools are needed so that designers can predict the impact of their design approaches on key process and performance attributes as well as other considerations, including manufacturing, operation, maintenance, warranty repairs/replacements, and environmental impacts. These tools need to show total costs in relation to changes in requirements, so that different "what-if" scenarios can be explored. "Smart" tools also are needed to aid development of tooling and production strategies. The capability to perform process development and qualification through software simulation would greatly reduce tooling costs. Similarly, virtual testing and simulation of as-designed and as-manufactured parts would reduce costs and detect problems without full-systems testing. A few essential, underpinning components of such intelligent tools are described below.

Comprehensive, Physics-Based Models of Processes and Network Models of Systems

Physics-based models are an essential foundation for all of the tools discussed. These models need to be verified and validated to establish confidence in their ability to provide accurate predictions of behaviors and results. Interface standards need to be established for linkages between the knowledge bases, analysis software, and automated processing equipment. Standards are needed for machine tools and other manufacturing equipment to report status and processing characteristics for analysis by operators and

managers so that they can optimize production. However, overall system performance is not a simple function of the performance of individual components. Research is needed to build models that more closely capture complex, nonlinear network behaviors.

Improved Optimization Capabilities for Better Decision Making

Improved decision making starts with selecting and using the right mathematical expression to properly combine multiple objectives. The right set of constraints needs to be incorporated as well, corresponding to external conditions such as environmental and other regulations. Elements of machining processes that are particularly ripe for optimization include tool path planning, scheduling and machine assignment, and plant layout. Moreover, a fundamental understanding is needed of how these lower-level decisions impact supply-chain goals such as cost-reduction targets. Tools are also needed to optimize the supply chain as a whole and to recommend contingency plans to minimize the impact of disruptions, both large-scale (e.g., a border closing or loss of a major transportation artery) and small-scale (e.g., equipment malfunctions).

Web-Based Tools to Enable Broader Participation in Manufacturing

Among the potential U.S. advantages in global manufacturing competition are a creative, entrepreneurial culture and a diverse and computer-savvy populace. Web-based software tools that hide detailed process-related information and allow design to be performed at increasingly high levels of abstraction have the potential to increase the engagement of a diverse cross-section of talents and perspectives in manufacturing and supply chain functions. In the electronic domain, such tools currently exist. They allow the automatic transformation of logic tables into plans for fabricating VLSI chips and bypass the need for the users of custom chips to have detailed understanding of how they are made. Such software tools have the potential to extend this capability into mechanical manufacturing and ultimately to the design and manufacture of future nanotechnology products.

Tools for Improving Development and Reducing the Life-Cycle Costs of Intelligent Embedded Systems in Manufactured Products

Embedded system software and other IT components have become key drivers of customer value and product differentiation, product life-cycle costs, and R&D investment and innovation for many manufactured products, including cars, planes, off-road equipment, appliances, and weapons systems. Such embedded intelligent systems add functionality to manufactured products as well as a means to monitor and diagnose the health and/or state of products. This represents a

fundamental shift for many manufacturing companies, which now perform as developers and integrators of products that rely on complex software systems to provide functional, safety, entertainment, and communications capabilities. Infrastructural tools and test methods are needed to enable embedded software advances, particularly in the areas of specification, validation, and certification.

Intelligent Systems for Manufacturing Processes and Equipment

The continuing exponential growth of computing power and the increasing availability of inexpensive, wireless, and networked sensors will soon deliver the technological horsepower required to build intelligent manufacturing processes and equipment with the ability to

- Know and communicate their capabilities, condition, and operational status
- Continually monitor, diagnose, and optimize all essential process parameters and their own performance
- Perform self-calibration and predict preventive maintenance tasks
- Know the quality of their work and can take steps to improve it
- Automatically capture, classify, and catalog process knowledge

- Flexibly build many variations of products in small, mixed quantities
- Discern patterns and trends that are beyond what humans can manage, and recommend appropriate responses to assist manufacturing knowledge workers in responding to complexity
- Be energy efficient and environmentally friendly
- Enhance worker safety and allow intuitive and robust human interaction

The technologies targeted for development in this category of R&D activities would make the leap from the predictive design capabilities discussed in the previous section to actual manufacturing process performance on the plant floor. Because the technologies envisioned here would possess the equivalent of a learning capacity, the results of data gathering, information analysis, and the resulting lessons “learned” would be used to inform future process designs and plans.

The industry-driven Integrated Manufacturing Technology Roadmapping Project report *Manufacturing Processes and Equipment* further elucidates the possibilities of intelligent manufacturing systems:

The information generated by the product/process design systems...will be directly downloaded to flexible processing equipment that will operate in a closed-loop environment to always deliver correct product... Intelligent controls integrated and interconnected at every level of production operation — regardless of geographic separation — will integrate information gathering, analysis, and processing functions into self-learning environments that address overall manufacturing performance and enable total process control... Future controllers will feature advanced functionality, modular designs, open architectures, and will be built on standard computing platforms that enable true plug-and-play integration... Process equipment will reach new levels of efficiency, reliability, and performance. Modular designs will shrink lead times for equipment purchase, reduce acquisition and maintenance costs, and lead to great efficiency in all types of manufacturing.³¹

While the above quote is from a report that was produced in the year 2000, many of the technologies and issues it identifies are still relevant today and remain as challenges that need to be addressed.

Manufacturing will need to become more highly instrumented and controlled, with more robust sensors and sensor processing algorithms providing “situational awareness” to production machines. Intelligent systems theory, as applied to manufacturing processes and equipment, will need to be expanded to include learning, automated reasoning, self-optimization, self-diagnosis, and adaptive control. These needs pose many technical challenges. Clearly, meeting these challenges necessitates greater understanding of how to transform real-time measurements, prior knowledge, and science and engineering principles into models for real-time sensory perception, automated decision making, and intelligent control. Development of automated techniques for classifying and cataloging data and knowledge will be required, as will be more powerful approaches for identifying and managing abnormal situations.

³¹ IMTI, Inc., *Integrated Manufacturing Technology Roadmapping Project: Manufacturing Processes and Equipment*, July 24, 2000, pp. 17–18, available at <http://www.imti21.org/resources/roadmaps.html>.

Automated Integration of Manufacturing Software

Currently, lack of interoperability among manufacturing software applications means that the process of integrating applications and systems within and across supply chain elements can consume substantial amounts of labor, time, and money. Making connections between different software applications requires human intervention on a case-by-case basis. Workers must analyze requirements and implement solutions based on their understanding of the meaning of the manufacturing information to be exchanged.

This can change, however, with the advent of the Semantic Web, which is one possible advance that will aid manufacturing. Simply stated, the Semantic Web is intended to enable computers to understand the meaning of concepts, to reason about those concepts, and to act on those concepts according to rules they have been given. This will require a new type of programming language that deals directly and only with the semantics, or meaning, of the information. The resulting programs will need to operate — and interact with one another — at the semantic level, not at the data level. This means, for example, that applications will need to know that purchase orders are different from schedules, which in turn are different from machine-tool programs; and they will need to know how to deal with those differences.

The Semantic Web promises to produce significant benefits for manufacturing. However, there are two important infrastructural questions to be resolved before these benefits accrue:

- First, what types of interface standards, modeling tools, and test methods will be needed tomorrow to capture and exchange the semantics that these new computer programs will use?
- Second, what types of standards, tools, tests, and methods are needed by manufacturers to instill today's technology with at least the beginnings of these semantic capabilities?

Realizing the goal of automating the integration of manufacturing software applications will require readily accessible design, manufacturing, and process data that are independent of vendor or data processing systems. Software tool sets for distributed engineering, manufacturing, and collaboration should be easily integrated and, therefore, based on open standards. Current integration efforts typically entail manual effort by systems engineers and programmers, which is slow, tedious, and error-prone.

At the other end of the integration spectrum is semantic-based self-integration, still a very long-term goal. Self-integration means that the entire integration process is completely automated. Ideally, self-integration could achieve higher levels of integration by performing computational tasks that are too complex for any person. However, both the theoretical and practical limits to self-integration are as yet unknown.

Considerable research in this area is needed. If it does prove possible and feasible, fully automated self-integration will be accomplished in stages. One step will be to develop a logically consistent set of tools to establish common computer-interpretable representations — ontologies — of the functions, data, and relationships associated with supply chain business processes, engineering design and analysis, production management, and shop floor processes.

While this need and others are being addressed, a pragmatic mid-term alternative to both manual and self-integration is to develop and apply automation methods wherever appropriate. This common-sense, yet still ambitious, approach has the potential to reduce labor costs while allowing the use of newer software, ontologies, and standards as they become available, creating a platform on which to build the next improvement in integration capabilities.

Secure Manufacturing Systems Integration

As manufacturing systems and supply chains become more interconnected and reliance upon computer control and optimization grows, there is a greater need to secure these systems against malicious attacks. There also is a great need to address national security concerns regarding the integrity of supply chains. Security is a key issue at every level, from production equipment networks and automation control systems to enterprises and supply chains. And new technologies — such as wireless communications and radio frequency identification (RFID) devices — promise landmark benefits but also introduce new potential vulnerabilities.

As IT and automated manufacturing operations advance and become simultaneously more diffuse and more integrated — as in the case of Web-enabled applications — additional vulnerabilities will be created. Consequently, appropriate security capabilities must be designed into systems from the start. Standards, performance metrics, and test methods are required for applying security technologies to real-time industrial control systems and supply chain transactions. Guidelines and tools must be established for making appropriate trade-offs between security, safety, and reliability. Security issues must be addressed throughout the entire life cycle of automation and supply chain communication systems, from the initial specification of requirements all the way through to design, construction, operation, maintenance, and decommissioning. Automated tools to test and verify the adequacy of security for complex, interconnected systems are sorely needed but do not currently exist.

Real-time computer control systems used in industrial control applications have many characteristics that differ from those of traditional information processing systems used in business applications. Foremost among these differences are design for efficiency and time-critical response. Process control systems that have been designed to meet performance, reliability, safety, and flexibility requirements typically were physically isolated and were based on proprietary hardware and communications. Computing resources available to perform security functions have tended to be very limited. The move toward centralized operation and remote maintenance of industry systems, combined with increased electronic supply chain interactions conducted over public

telecommunication networks, have resulted in potential security weaknesses that can be exploited to disrupt operations. Furthermore, the goals of safety and security sometimes conflict in the design and operation of industrial control systems.

The introduction of Internet-based IT and enterprise-integration strategies coupled with lack of IT security knowledge has left some process control systems vulnerable to cyber-based attacks. In some cases, control networks have been connected to corporate networks to allow engineers to monitor and control systems from points on the corporate network. IT mechanisms also are in place to allow corporate decision makers to obtain instant access to critical data. Such network architecture modifications, if implemented without a full understanding of the corresponding security risks, can lead to control networks that are only as secure as the corporate network.

Validation of the significance and difficulty of these issues can be found in many cybersecurity plans and reports, including a November 2005 *Hard Problem List* issued by the INFOSEC Research Council, a multi-agency Federal forum for discussing and responding to critical information security issues. The list identifies availability of real-time systems as challenge number three (of eight total):

*The threats to time-critical systems are even more notable than those for conventional systems. System, network, and enterprise survivability critically depend not only on security, but also on reliability and fault tolerance, and the ability to recover sufficiently rapidly from outages and from losses or diminution of resources. ... Moreover, demand for time-critical processing is growing rapidly in environments that use robotics, RFID, and sensor networks for real-time data collection.*³²

Factory production and automation control systems fall squarely in this category and are emblematic of these characteristics and challenges.

³² INFOSEC Research Council, *Hard Problem List*, November 2005, pp.16–17, available online at <http://faculty.business.utsa.edu/amcleod/SwA/IRC-HPL-20051130.pdf>.

R&D Opportunity Areas

An extensive review of federal manufacturing technology R&D projects was conducted in 2000.³³ Although information technology has advanced significantly since then, several research opportunities identified in that analysis correspond closely to the major challenges summarized earlier in this chapter. A number of topics warrant emphasis on intelligent and integrated manufacturing:

- Integrated product and process design
- Common, extendable reference architectures and frameworks
- Unified manufacturing information infrastructure
- Manufacturing knowledge repositories
- Plug-and-play manufacturing information systems
- Flexible, complex representation
- Distributed product modeling collaboration environment
- Robust cost modeling
- Broad-based material modeling framework
- Full-time, 100% availability of IT systems
- Flexible, reconfigurable distributed enterprise operation
- Top-level optimization of product, process, and resources
- Seamless data and application interoperability

The Federal R&D efforts described in the previous section provide important foundational capabilities for intelligent and integrated manufacturing, with some of the NITRD activities directly addressing manufacturing problems and needs. However, there is an opportunity for the IWG to raise the visibility of manufacturing issues and challenges as target applications within the NITRD Program. This can be accomplished through increased IWG participation in NITRD planning and coordination activities. Cross-fertilization of ideas and approaches also can be encouraged through participation of NITRD Program representatives in the activities of the IWG on Manufacturing R&D.

Recommendations and Next Steps for the IWG

There is a clear opportunity to gain greater leverage, reduce potential duplication of effort, and increase the long-term contributions of Federal research to the performance and competitiveness of U.S. manufacturing. This can be achieved through increased coordination of Federal R&D activities in the area of intelligent and integrated manufacturing. While this chapter provides an important starting point for defining R&D needs, challenges, and gaps in this critically important area, it is only that — a start. Much remains to be done, including further refinement of ideas to incorporate industry input, develop more effective mechanisms for sharing information, and coordinate efforts across agencies.

There are a number of industry-led R&D initiatives in intelligent and integrated manufacturing. Member agencies of the

³³ Integrated Manufacturing Technology Initiative, Inc. (IMTI), *Manufacturing Success in the 21st Century: A Strategic View*, Oak Ridge, TN: IMTI, July 2000.

IWG intend to participate as partners in such efforts, identifying appropriate Federal sector and specific agency roles and using these collaborations to update and adjust research priorities in response to evolving industry needs and emerging technological opportunities.

The IWG proposes to establish an Intelligent and Integrated Manufacturing Subgroup to facilitate these interactions through the following kinds of activities:

- Hold workshops and planning events to further define and refine intelligent and integrated manufacturing R&D needs and priorities
- Implement mechanisms for sharing tools and technologies across agencies (including interagency program reviews, Web repositories, and testbeds) to obtain maximum leveraging of results and to avoid duplication of effort
- Coordinate cross-participation in relevant NITRD Coordinating and Interagency Working Groups to ensure manufacturing needs and priorities are represented in these R&D portfolios
- Participate in the Manufacturing R&D for Hydrogen Technologies and Nanomanufacturing activities of this IWG to provide expertise and input related to intelligent sensing, modeling, and control, as will be needed for new manufacturing processes required in both priority areas

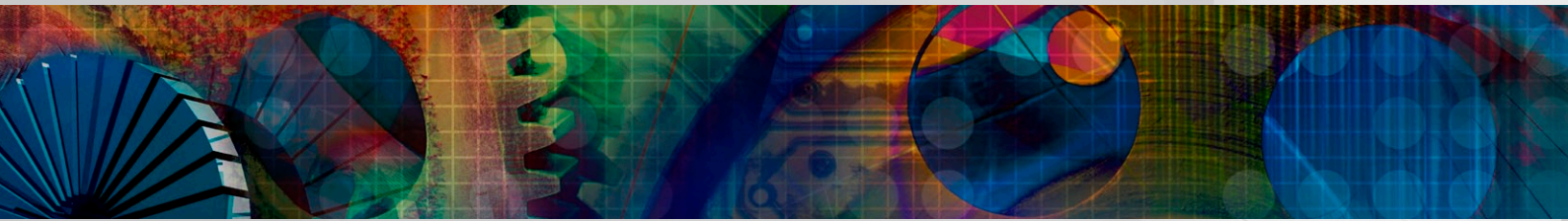
- Identify state-level research efforts and economic development activities related to the Intelligent and Integrated Manufacturing priority area, and establish mechanisms for sharing plans and results with Federal agencies

In carrying out these activities, the IWG plans to identify technical approaches that can yield broad impacts across many manufacturing sectors (or groups of related sectors).

Finally, the IWG believes there is a major opportunity for the manufacturing community to benefit from theories and technologies arising from seemingly disparate fields, such as mathematics, economics, operations research, decision theory, game theory, artificial intelligence, pattern recognition, and many others. Similarly, theories and practices developed within the discipline of manufacturing — lean manufacturing and six sigma processes, for example — can provide benefits in other domains. Comparing and validating theories and results across domains provide important opportunities to learn new things and inspire innovation. When researchers and practitioners are exposed to theories and research from different disciplines, the result often is deeper understanding and new insights on all sides. The IWG will help to facilitate such interactions by conducting workshops specifically designed to provide opportunities for people, ideas, and results to cross disciplinary boundaries.

Chapter 5

Cross-Cutting Issues



The three manufacturing technical priority areas described in chapters 2-4 point toward a manufacturing future that is more highly technical, sophisticated, and dynamic. As R&D creates that future, the technological changes will be accompanied by issues associated with

- Preparing and educating the future manufacturing workforce
- Ensuring human health and safety
- Fostering environmental sustainability
- Developing effective standards

This chapter addresses these four issues, which are keys to the ability of industry and the Nation to develop, apply, and derive social and economic value from the new technologies to come.

Preparing the Manufacturing Workforce of the Future

Many manufacturing industries are undergoing dramatic transformation in terms of equipment, market dynamics, workforce demographics, and skills needed to work in their modern production facilities. To remain viable in the face of intense global competition, U.S. manufacturing establishments are increasingly high-tech enterprises. Successful manufacturers are implementing process improvements, increasing quality controls, and installing advanced robotics and other intelligent production systems. These translate into advantages in terms of speed to market, operational flexibility, mass-customization, and higher quality. Companies that have realized these advantages tend to be more competitive through greater productivity and by delivering greater value to customers. This transformation has profound implications for both the current and future manufacturing workforces. Increasingly, manufacturers require workers with advanced skills.

Skills Requirements for Workers

In its 2005 skills gap survey of more than 800 manufacturing businesses, the National Association of Manufacturers (NAM) found that 81% were experiencing “severe” (13%) or “moderate” (68%) shortages of skilled workers overall, and 90% reported shortages of skilled production employees.³⁴ On the basis of this and other findings, the NAM report concludes that the shortages are “causing significant impact to business and the ability of the country as a whole to compete in a global economy.” Indeed, three-fourths of respondents cited a “high-performance workforce” as a key driver of future business success. Manufacturers ranked “new product innovation” as second on the list of most important determinants of success, which the report described as “inextricably linked to employee quality.”³⁵

The limited availability of qualified workers is likely to be exacerbated by the expected surge in retirements within the next several years as workers from the “baby boomer” generation depart the workforce. While new technologies will require new skills, the loss of knowledge and expertise that comes with the retirement of long-term, qualified employees could present challenges.

To operate a modern production facility, manufacturers require workers with adequate preparation in fundamentals such as mathematics, science, reading comprehension, and writing; strong workplace competencies, including computer literacy, teamwork, and critical thinking; and technical competencies in areas such as quality and process control, supply chain management, and integrated production systems. Manufacturing workers may also need to develop specialized skills tailored to specific jobs, industrial needs, and technology requirements, necessitating further education and training. Today, experienced workers with advanced skills are in high demand and vital to a company’s growth.

Manufacturing skills certification is one of several steps toward ensuring an adequate supply of “knowledge technologists,” a term coined by management and quality pioneer Peter Drucker. In future manufacturing operations, as well as in other sectors of the economy, Drucker predicted, workers will continue to engage in manual tasks, but their jobs will require a “substantial amount of theoretical knowledge which can only be acquired through a formal education, not through an apprenticeship.”³⁶

³⁴ National Association of Manufacturers and Deloitte Development LLC, *2005 Skills Gap Report — A Survey of the American Workforce*, 2005, available at <http://www.nam.org/2005skillsgap>.

³⁵ *2005 Skills Gap Report*, *op. cit.*

³⁶ Peter Drucker, *The Next Society*, *The Economist*, Nov. 1, 2001.

The challenges of attracting qualified workers, retaining experienced personnel, and training incumbent workers to keep their skills current will persist throughout the U.S. manufacturing sector's enterprises, from small, specialized suppliers to large, diversified original equipment manufacturers. Although productivity improvements and other factors will influence future demand for production and affiliated workers, the manufacturing sector will continue to be a major employer, and its success will depend on access to an innovative, technology-savvy, highly skilled workforce.

Manufacturers recognize the need to establish frameworks of foundational skills and competencies that future workers must possess if companies and industries are to master advanced manufacturing and business methods and compete effectively in 21st Century manufacturing. Moreover, prospective workers need to know what skills they should have to make the first step toward a successful career in manufacturing. Educators and training providers need to know appropriate training standards, and that those standards are directly relevant to industry requirements. Finally, government officials need to know that training programs they support are producing workers who can find relevant employment.

Higher Education in Science and Engineering

The competitiveness of U.S. manufacturing industries is tied directly to the sector's success in developing and applying new technologies, which in turn depends on the future supply of scientists and engineers. Numerous reports have expressed concern about low student enrollments in engineering and the physical sciences. They point to American students' declining interest in these fields and the fact that foreign students account for significant graduate enrollments in the physical sciences, mathematics and computer science, and engineering.

From 1983 to 2001, enrollment in U.S. institutions of higher education rose from 12.6 million to 15.7 million students.³⁷ Over that same period, the number of entering freshman who declared their intent to study science and engineering, as well as the percentage of degrees conferred in these areas, remained steady at about one-third of all degrees. More recently, among students who graduate with science and engineering bachelor's degrees, the retention rate of those who go into science and engineering graduate education or careers has declined to 28%.³⁸ However, since 2001, the total number of science and engineering degrees awarded at U.S. universities is rising, according to the National Science Board report, *Science and Engineering Indicators 2006*.³⁹

³⁷ American Competitiveness Initiative, *op. cit.*, p.20

³⁸ *Ibid.*

³⁹ National Science Board, *Science and Engineering Indicators 2006*. Two volumes. Arlington, VA: National Science Foundation, 2006 (volume 1, NSB 06-01; volume 2, NSB 06-01A).

While not an indication of education quality, enrollment trends in other countries are interesting. For example, in Germany the percentage of undergraduates receiving their degrees in science and engineering is similar to the U.S. percentage, whereas in China and Japan the percentages are much higher.⁴⁰

Education, training, creativity, and innovation will be the key attributes for the entire manufacturing workforce, including the workforce associated with the three IWG technical priority topics. As related to nanomanufacturing in particular but also true for the other two focus areas, new interdisciplinary curricula are needed to better prepare teachers and students to enter the labor markets likely to grow around new, emerging industries.

Overall, a strong educational infrastructure is needed to enable and shape new research directions. The full range of the manufacturing workforce beyond scientists and engineers will need to have a strong technical education, be comfortable with IT and automated systems, and have the skills and mindset to continuously learn new things. Many questions persist about the adequacy of the future supply of “knowledge technologists” for tomorrow’s front-end manufacturing operations and of science and technology personnel to perform R&D.

Federal Responses and Leadership

The Federal Government is addressing these challenges. The American Competitiveness Initiative contains both a Workforce Training Initiative and an Education Initiative. Additionally, a working group of industry representatives, educators, and staff from the Department of Labor Employment and Training Administration has developed a dynamic, industry-driven framework for the basic knowledge, skills, and abilities that are necessary for entry-level workers across all manufacturing sectors. The DOL/ETA working group reviewed hundreds of existing industry standards and curricula to identify those common elements. In this way, their framework builds on, and aligns with, the excellent work that has already been done by many groups but which has never been assembled into a comprehensive model. Such a model framework allows for consistency across industries, customization within sectors, and easy updating to accommodate changing technology and business practices. It provides a common language and a reference that will facilitate communication as industry leaders, educators, and other stakeholders implement a variety of workforce development activities:

⁴⁰ Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology, National Academy of Sciences, National Academy of Engineering, Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press, 2005, available online at http://www.nap.edu/catalog.php?record_id=11463#toc.

- Sector-specific competencies that flow from the foundational competencies
- Competency-based curriculum and training models
- Position descriptions and hiring criteria for industry
- Assessment and testing instruments
- Guidance for government investments in workforce preparation strategies for the manufacturing sector

NSF's Advanced Technological Education program⁴¹ focuses on the education of technicians in high-technology fields that drive the Nation's economy. Partnerships with community colleges are a major emphasis. The program supports curriculum development, professional development of college faculty and secondary school teachers, and career pathways to two-year colleges from secondary schools and from two-year colleges to four-year institutions. For example, an NSF grant in 2005 to a Wisconsin technical college is being used to reformulate and update the science, technology, engineering, and mathematics-related programming at the two-year institution to meet the needs of area employers. This effort includes an assessment of how current and future learning systems should respond to changes in the workplace. This guiding activity, which is intended as a pilot for Wisconsin's entire technical college system, is being carried out with input from both employers and university faculty.

Other programs at NSF invest in the preparation of a highly qualified scientific and technical workforce at all levels, from K-12 through post-graduate. These include programs in the Directorate for Education and Human Resources, such as the Math and Science Partnership program, Noyce Scholarships, Graduate Research Fellowships, Louis Stokes Alliances for Minority Participation, and Discovery Research K-12, as well as other educational efforts in the research directorates throughout the Foundation.

DOL is leveraging Federal and private resources to design innovative education and job training programs. Under the President's High Growth Job Training Initiative (HGJTI), DOL is addressing critical workforce needs in advanced manufacturing operations.⁴² Administered by the Department's Employment and Training Administration, the program is following a strategy of collaboration with employers, schools, and economic development organizations. The aim is to develop and demonstrate partnership-based solutions that can be replicated across the country. This approach recognizes that although the Federal Government invests, economy-wide, about \$15 billion annually in workforce development programs, the bulk of funding for training and related programs comes from the private sector.

⁴¹ See http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5464&org=NSF&from=fund.

⁴² For more information on the advanced manufacturing component of the President's High Growth Job Training Initiative, go to <http://www.doleta.gov/BRG/Indprof/Manufacturing.cfm>.

The HGJTI is demonstrating how these partnerships can prepare workers for job opportunities in high-growth, high-demand sectors of the American economy. It focuses on workforce development for advanced manufacturing, one of the priority industries targeted by the HGJTI. These efforts are addressing three categories of need: capacity building, “pipeline” development, and training for innovation.

In addition, DOL has launched the Workforce Innovation in Regional Economic Development (WIRED) Initiative,⁴³ which focuses on the role of talent development in driving regional economic competitiveness, job growth, and creation of new opportunities for American workers. The WIRED Initiative concentrates on labor market areas that are comprised of multiple jurisdictions within state or across state borders. Through the WIRED Initiative, DOL has invested \$325 million in 39 regional economies to support innovative approaches to education and workforce development. These approaches go beyond traditional strategies as they prepare workers to compete and succeed, both within the United States and globally.

Through the WIRED Initiative, state governors have a unique opportunity to design and implement strategic approaches to regional economic development and job growth. The WIRED Initiative is intended to catalyze the creation of high-skill and high-wage opportunities for American workers within the context of regional economies.

This initiative is designed for regions that have been adversely affected by global trade, are dependent on a single industry, or are recovering from natural disasters. Demonstration projects are a central part of the WIRED strategy, and these are carried out in a number of regions whose economies depend significantly on a competitive manufacturing workforce.

The Department of Education (ED), through the No Child Left Behind Act, the Science and Math Partnerships Program, the State Scholars Initiative, and the President’s American Competitiveness Initiative, is making a major effort to better prepare students for the rigors of post-secondary education and the increasingly demanding expectations of employers.

The ED Office of Vocational and Adult Education, through the College and Career Transitions Initiative, is supporting the implementation of career pathways that outline a rigorous sequence of both academic and technical courses aligned with the expectations of post-secondary education and employers. Career pathways are organized around a set of 16 career clusters, two of which directly connect students to careers in manufacturing: Science, Technology, Engineering and Mathematics (STEM); and Manufacturing.

Within the Federal Government as a whole, many of these workforce educational issues are being addressed from a multiagency perspective by the NSTC’s Interagency Working Group on Manufacturing Competitiveness. This IWG was created in response to the *Manufacturing in America* report; it has participation from 17 Federal agencies and includes a subcommittee on workforce education and development.

⁴³ See <http://www.doleta.gov/wired/>.

In sum, advanced manufacturing capabilities are a necessity for innovation-driven economic growth, and education is the foundation of a knowledge-based, innovation-driven economy. For the United States to maintain its global economic leadership, we must work harder and smarter to ensure that there exists an adequate supply of highly trained mathematicians, scientists, engineers, technicians, and scientific support staff, and that this educational pipeline is enabled by a scientifically, technically, and numerically literate population. The Nation's response to these concerns will bear significantly on the long-term performance of U.S. manufacturers and their success in the global economy.

Ensuring Health and Safety

Many uncertainties surround emerging technologies, from speculation about prospective applications and markets to unknown risks and hazards.

With regard to the three priority areas identified by the IWG on Manufacturing R&D, two — Manufacturing for the Hydrogen Economy and Nanomanufacturing — particularly warrant proactive attention to environmental, health, and safety (EHS) issues. Through agencies participating in the IWG and through its interactions with other Federal bodies and activities, the IWG is proceeding with full appreciation of their importance. It recognizes that these issues must be resolved to the satisfaction of regulators, workers, and the general public.

Manufacturing R&D for Hydrogen Technologies

The challenges to making hydrogen a practical commodity for energy applications, particularly transportation, are many. Major advances are needed before we reach the goal of large-scale hydrogen production, storage, delivery, and use.

A critical cross-cutting challenge is ensuring safety across the hydrogen infrastructure — from production through use in automobiles, homes, and businesses. As is true for all fuels, the same energetic properties that make hydrogen useful as a source of power also require that we handle it with appropriate safeguards. Today's cars and trucks and all fuel production and distribution systems have built-in safety systems. Tomorrow's hydrogen-powered vehicles and the underlying infrastructure will require the same. Current uses of hydrogen in industry demonstrate that hydrogen can be handled and used safely with appropriate sensing, handling, and engineering measures.

Safety-related issues will have a high profile during ongoing R&D efforts aiming for commercialization of hydrogen systems within the next two decades. The Department of Energy and the Department of Transportation, working with industrial and international partners, are proactively addressing these question and concerns within their mission-related areas of responsibility. Their participation on the IWG assures that manufacturing-related technologies being pursued in support of hydrogen goals will fully reckon with safety-related issues and contribute to effective solutions.

In November 2005, DOT issued its “hydrogen roadmap,”⁴⁴ the Department’s guiding document for its Hydrogen Safety Research, Development, Demonstration, and Deployment programs. Safety codes, standards, and regulations constitute one of four major component areas of the roadmap, while safety education, outreach, and training constitute another. The guidance applies to appropriate handling and use of hydrogen across all modes of transportation.

Nanomanufacturing

In the area of nanotechnology, the IWG will work with the NSET Subcommittee of the NSTC on a variety of health and safety issues, including research on potential risks. In order to support Federal activities to protect public health and the environment, the NSET Subcommittee created the Nanotechnology Environmental and Health Implications (NEHI) Working Group in 2003 with the purpose, among other things, of facilitating the identification, prioritization, and implementation of research and other activities required for the responsible research, development, utilization, and oversight of nanotechnology. Through the NEHI Working Group (See membership list, Table 5-1), agencies exchange information and identify research needed to support regulatory decisions. The NEHI Working Group promotes communication regarding the environmental and health implications of new nanomanufacturing technologies.

Table 5-1: NEHI Membership

Consumer Product Safety Commission
Department of Agriculture
Department of Defense
Department of Energy
Department of Transportation
Environmental Protection Agency
Food and Drug Administration
National Aeronautics and Space Administration
National Institute of Environmental Health Sciences
National Institute for Occupational Safety and Health
National Institute of Standards and Technology
Occupational Safety and Health Administration
Office of Management and Budget
Office of Science and Technology Policy

⁴⁴ US Department of Transportation, *Research, Development, Demonstration, and Deployment for Hydrogen Vehicles and Infrastructure to Support a Transition to a Hydrogen Economy*, October 2005, available at <http://hydrogen.dot.gov>.

In September 2006, the NSET Subcommittee of the NSTC published a report, *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials*, to identify for the Federal Government the EHS research and information needs related to understanding and management of potential risks of engineered nanoscale materials that may be used in commercial or consumer products, medical treatments, environmental applications, research, or elsewhere.⁴⁵ The NEHI Working Group is in the process of developing a research strategy for addressing the needs identified in this report.

In addition, the Environmental Protection Agency, a member of the IWG, has been actively researching approaches to risk assessment. This effort includes identifying crucial voids in understanding as well as evaluating the applicability of established methods and procedures for risk assessments of emerging nanotechnology products and processes. In February 2007, EPA published its *Nanotechnology White Paper*⁴⁶ identifying key questions for EPA to address as nanotechnology is developed. The agency will use it to help focus on nanotechnology research and risk assessment priorities.

There are many unanswered questions about the effects of new nanomanufacturing technology:

- Do nanoscale materials pose hazards different than those produced by the same material in conventional form?
- If nanoscale materials do pose hazards, what are the long-term effects of exposure to these types of hazards?
- Can exposure risks be reduced to acceptable levels?

DOL's Occupational Safety and Health Administration (OSHA), EPA, and other Federal agencies with regulatory or research responsibilities are collaborating to address these and other health and safety concerns relating to the mass-production and commercial use of nanoscale materials.

One program specifically focused on effects of nanotechnology on human health is the National Toxicology Program (NTP). The NTP is a partnership of National Institute of Environmental Health Sciences (NIEHS) at NIH, the National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control and Prevention, and the National Center for Toxicological Research (NCTR) of the Food and Drug Administration (FDA). One of the lead programs under the NTP will address potential human health hazards from unintentional exposure associated with the manufacture and use of nanoscale materials, especially those of current or projected commercial importance. The overall goal of the NTP safety initiative for manufactured nanomaterials is to understand critical physical and chemical properties that affect biocompatibility so that in the future, nanomaterials can be designed to minimize adverse health and safety outcomes.

⁴⁵ National Science and Technology Council, National Science, Engineering, and Technology Subcommittee, *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials*, September 2006, available at http://nano.gov/NNI_EHS_research_needs.pdf.

⁴⁶ EPA Nanotechnology Workgroup, *U.S. Environmental Protection Agency Nanotechnology White Paper*, EPA100B-07/001, February 2007, available at <http://www.epa.gov/osa/pdfs/nanotech/epa-nanotechnology-white-paper-final-february-2007.pdf>.

Most of the funding for this NTP activity is contributed by NIEHS. The NCTR contributes the use of state-of-the-art capabilities at its Phototoxicology Center. Studies are underway examining the absorption, biological fate, and potential toxicity of quantum dots, metal oxides used in sunscreens, and selected carbon-based materials (e.g., fullerenes and carbon nanotubes), following application to the skin or exposure by inhalation or ingestion. The NTP is also coordinating its activities with the health and safety programs of the National Cancer Institute's Nanotechnology Characterization Laboratory to ensure the most efficient development of nanoscale cancer therapeutics that are both safe and effective.

Additionally, NIEHS is participating with EPA, NIOSH, and NSF in funding a joint effort to investigate environmental and human health effects of manufactured nanomaterials. Research areas include the toxicology, fate, transport and transformation, and bioavailability of nanomaterials, along with exposures of human and other species in natural ecosystems to nanomaterials, and industrial ecology related to nanomaterials.

The Federal Government also is contributing to an ISO effort to develop standards for nanotechnology. The U.S. delegation, accredited by the American National Standards Institute, is led by the director of the National Nanotechnology Coordination Office. At the inaugural meeting of ISO Technical Committee 229, Nanotechnologies, held in November 2005, the United States was chosen to lead the ISO committee's working group on health, safety and the environment.

Fostering Environmental Sustainability

To stay competitive, manufacturers must continually increase efficiency and productivity. The constant quest for greater efficiency yields benefits that extend beyond individual firms. By reducing resource use, waste streams, water consumption, and energy consumption, efficiency measures, if carefully designed to do so, also reduce the size of the manufacturing sector's environmental footprint.

R&D efforts in the three priority areas identified by the IWG can foster manufacturing practices that have significant environmental benefit in terms of

- Reducing the material intensity of production and consumption
- Substituting environmentally preferable materials for hazardous ones
- Minimizing waste and emissions throughout the cycle life
- Increasing energy efficiency throughout the product life cycle
- Enabling large-scale transition to renewable sources of energy and feedstocks
- Maximizing recovery or reuse at the end of the product life cycle

The benefits of more efficient manufacturing operations can extend beyond the environment. Potential benefits can also include cost savings, reductions in product development time, improvement in workplace safety, and simplified compliance with international environmental regulations or customer demands for improved environmental management systems.

The promise of hydrogen fuel cells illustrates the “win-win” possibilities that continuing technological progress can place within the Nation’s reach. Practical, affordable fuel cell technology can reduce emissions of air pollutants and greenhouse gases and provide an efficient substitute for petroleum. These benefits, in turn, will help to realize sustained growth in domestic and global car sales, minimized environmental impacts with even more cars on the road, and adherence to regulatory requirements.

However, it is important to support research that enables the understanding and optimization of the full life cycle impacts of hydrogen and fuel cell technologies, such that a win-win scenario at the use phase is not countered, for example, by energy- and materials-intensive manufacturing practices.

The multidisciplinary realm of nanotechnology offers potential opportunities to address persisting environmental challenges, such as the clean-up of hazardous waste sites, to reduce industry’s consumption of materials and energy, as well as to reduce its waste streams — potentially in significant amounts. Capabilities for molecular-scale manipulation and control will enable the design of materials and devices that have desired properties for specific applications. Such customization, combined with

miniaturization, could potentially reduce the materials intensity of manufacturing. It may also open new avenues to improving energy efficiency, eliminating or treating waste, and purifying water.

Similarly, information technology offers the potential (as yet unrealized) to further the aim of sustainable growth in the manufacturing sector and the economy as a whole. More powerful information technology application can help individual manufacturers and inter-firm networks perform more efficiently and more productively with less resource intensity and, overall, with far less environmental impact. Information technology provides powerful, versatile tools that still are far from optimization. Significant improvements are needed so that businesses, their suppliers, and their customers can increase the intelligence and interoperability of their systems and processes.

Better modeling and simulation tools, for example, will advance efforts to design waste-free — and error-free — manufacturing processes and to assess how substituting new environmentally benign materials will affect the performance of products. Intelligent interconnected systems can facilitate development of products and technologies appropriate to local needs, tastes, and environmental conditions. By eliminating barriers to cooperation on local and international scales, interoperable networks can facilitate more rapid diffusion of best practices to achieve environmentally benign manufacturing operations across supply chains and to address sustainability issues from design all the way through to the end of a product’s service and even beyond to repair, recycling, or reuse.

In summary, there are opportunities for research to inform sustainable manufacturing technologies at all levels of manufacturing research: unit process, machine, systems, and society. For all emerging manufacturing domains, the development of sustainable unit processes can protect the environment as well as lower costs. Machine systems that are flexible, energy-efficient, and conserving of materials can have these results; and at a systems level, manufacturing approaches that reduce the number of processes required can yield environmental benefits, as well as reductions in overall manufacturing time. Additionally, system-level sensors, information, and communication technologies that link elements of a supply and/or recycling chain can enable an additional layer of environmental optimization. Finally, at the societal level, a better understanding of the coupling of manufacturing with societal infrastructure may lead to opportunities to improve environmental performance system-wide, such as through optimized, energy-efficient transportation logistics.

Developing Effective Standards

Standards are agreed-upon technical specifications designed to ensure that a product, process, or service is fit for its intended purpose. They are fundamental to the application and diffusion (including marketing) of new technologies and the products based upon them. Demanded by customers or embodied in regulations, standards impact an estimated 80% of global commodity trade.⁴⁷ In so doing, standards have earned a checkered reputation. As explained in a 2004 report by the Department of Commerce, “Standards are a critical issue for manufacturing competitiveness in global markets, as they can facilitate international trade, or they may impede access to foreign markets. Many in U.S. industries view standards as the principal non-tariff barriers around the world.”⁴⁸

Standards are necessary for several purposes and uses. These range from enlarging markets and enabling economies of scale in manufacturing to ensuring efficacy, reliability, safety, environmental quality, and compatibility with interfacing products. Given the increasing complexity and system-like nature of modern technologies, interface standards that enable compatibility and interoperability have grown immensely in utility and importance.

⁴⁷ Department of Commerce, *Standards & Competitiveness: Coordinating for Results, Removing Standards-Related Trade Barriers through Effective Collaboration*, May 2004, p. 1, available at http://ts.nist.gov/Standards/upload/trade_barriers_report-2.pdf.

⁴⁸ *Ibid.*

It is strategically important that competitors — nations, industries, and businesses — ascribe to these technical standards and specifications. Traditionally, being first in the development of a new advanced technology — be it in the realm of aerospace, magnetic data storage, or any other “high-tech” industry — conferred a leadership position in the development of the associated standards, which, as noted previously, influence market size and access.

However, country-to-country (or region-to-region) differences in the technical requirements of standards developed for similar purposes or in legally prescribed methods for determining conformance to the same standard sometimes can cause inefficiencies and pose market barriers. Today, standards development can be a highly contested process. And standards development frequently takes place simultaneously in several different venues — from domestic consortia to regional and international organizations. In fast-paced technology areas, many companies — especially small and medium-sized ones — worry about being blindsided by new standards or regulatory requirements that can influence their access to markets and increase their cost of doing business.

As discussed in the section on health and safety, the Federal Government — and, in particular, IWG member agencies — are facilitating industry involvement and proactive U.S. participation in the development of standards related to hydrogen-power and nanotechnology applications. Although still “emerging” areas of technology, both fields are progressing, and both are the objects of intensifying international efforts. Technically sound anticipatory standards could speed progress, instill public confidence, and, ultimately, foster commercialization and practical application on an international scale.

Related to hydrogen-based systems and products, DOE is coordinating a collaborative national effort by government and industry to prepare, review, and promulgate model hydrogen codes and standards to expedite hydrogen infrastructure development. Working in close partnership with the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee,⁴⁹ this DOE group communicates and cooperates with the diverse public and private organizations that make up the hydrogen community. These collaborations work toward the development of consistent codes and standards to accelerate the commercialization of fuel cell and other hydrogen technologies. Safety is a major emphasis of these activities, since it is essential to public acceptance of the emerging technology. Standards specifying requirements for testing, certification, and comprehensive safety assessments are examples.

⁴⁹ Formed in March 2005, the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee combines three separate organizations: DOE Hydrogen Codes and Standards Coordinating Committee, the U.S. Fuel Cell Council's Codes and Standards Working Group, and the National Hydrogen Association Codes and Standards Committee.

Activities often extend to the international level. For example, DOE and its partners have been working through the International Partnership for the Hydrogen Economy under the auspices of the International Code Council to develop model building codes that address hydrogen as an energy carrier and incorporate provisions that include fuel cells as generating devices or appliances.

Moreover, the Department of Commerce's Standards Initiative, launched in 2004, has spawned actions intended to increase the effectiveness of Federal programs that can aid in championing U.S.-developed technology solutions for adoption as standards by international bodies. NIST, a member of the IWG, has served as the lead on a number of these activities. NIST scientists and engineers represent U.S. interests in some 180 international standards committees and international industrial consortia. The agency is working with other government agencies and with the American National Standards Institute (ANSI) and its members to target critical activities in standards organizations so as to avoid adoption of international product standards that are technical barriers for U.S. exports.

In 2006, NIST and ANSI hosted a meeting for standards developers and industry and government representatives to develop timetables and actions that can be taken to make the United States more competitive in the international standards arena. Participants worked together on devising methods to coordinate and leverage the resources of individual organizations to respond more effectively to external standards-related challenges to innovation and competitiveness.

Ideally, standards should be established collaboratively, based on the results of the best science, the best technology, and the best knowledge derived from experience, and have the aim of maximizing the benefits of innovation to society.

Appendix: List of Acronyms

ACI	American Competitiveness Initiative of the President
AML	Advanced Measurement Laboratory (NIST)
ANSI	American National Standards Institute
BOP	balance-of-plant
Btu	British thermal units
CBAN	NNI Consultative Boards to Advance Nanotechnology
CNST	Center for Nanoscale Science and Technology (NIST)
CSREES	Cooperative State Research, Education, and Extension Service (USDA)
CT	Committee on Technology of the NSTC
DHHS	U.S. Department of Health & Human Services
DHS	U.S. Department of Homeland Security
DHS S&T	Department of Homeland Security Science and Technology Directorate
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
DOT	U.S. Department of Transportation
ED	U.S. Department of Education
EERE	Office of Energy Efficiency and Renewable Energy of DOE
EHS	environment(al), health, and safety
EPA	U.S. Environmental Protection Agency
ETA	Employment and Training Administration (DOL)
FDA	U.S. Food and Drug Administration
FY	fiscal year
GDP	gross domestic product
HGJTI	High Growth Job Training Initiative of the President
IEEE	Institute of Electrical and Electronics Engineers
IIM	intelligent and integrated manufacturing
ISO	International Organization for Standardization
IT	information technology
ITA	International Trade Administration (DOC)
IWG	Interagency Working Group (in this report, the Interagency Working Group on Manufacturing R&D)

kWh	kilowatt-hours
MAS	Manufacturing and Services unit of DOC
MEA	membrane electrode assembly
MEMS	microelectromechanical systems
MSFC	Marshall Space Flight Center (NASA)
Nano-CEMMS	Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems at the University of Illinois at Urbana-Champaign
NASA	National Aeronautics and Space Administration
NCTR	National Center for Toxicological Research (FDA)
NDE	nondestructive evaluation
NDT	nondestructive techniques
NEHI	Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee
NIEHS	National Institute of Environmental Health Sciences (NIH)
NIH	National Institutes of Health of DHHS
NIOSH	National Institute for Occupational Safety and Health at the Centers for Disease Control and Prevention
NIST	National Institute of Standards and Technology (DOC)
NITRD	Networking and Information Technology Research and Development program of the NSTC
NNCO	National Nanotechnology Coordination Office of the NSET
NNI	National Nanotechnology Initiative
NNSA	National Nuclear Security Administration (DOE)
NSEC	Nanoscale Science and Engineering Center (NSF)
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSF	National Science Foundation
NSRC	Nanoscale Science Research Center (DOE)
NSTC	National Science and Technology Council
NTP	National Toxicology Program, a partnership of NIEHS, NIOSH, and NCTR
OET	Office of Educational Technology of ED
OGCBD	SBA's Office of Government Contracting and Business Development
OMB	Office of Management and Budget
ORD	Office of Research and Development (EPA)
OSD	Office of the Secretary of Defense
OSTP	Office of Science and Technology Policy (Executive Office of the President)

PCA	program component area
PCAST	President's Council of Advisors on Science and Technology
PEM	polymer electrolyte membrane (also proton exchange membrane)
R&D	research and development
RFID	radio frequency identification
RITA	Research and Innovative Technology Administration (DOT)
SBA	U.S. Small Business Administration
SBIR/STTR	Small Business Innovation Research and Small Business Technology Transfer initiatives, administered through the SBA Office of Technology
SINAM	UCLA Center for Scalable and Integrated NanoManufacturing
UCD	unified cell device,
USDA	U.S. Department of Agriculture
WIRED	Workforce Innovation in Regional Economic Development initiative (DOL)

